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TOWARDS A PRODUCTIVE ARCHITECTURE

High-tech food prodction technologies integrated in Architecture for the implementation of new circular Urban Agriculture models

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Abstract

Urban Agriculture has seen a growing interest in recent years and planners, engineers, and architects joined agronomists in proposing farming projects within the cities' boundaries. The reason for the recent success of UA is not only to be found in its ability to increase global food production but also in its possibility to implement targeted circular flows of resources in urban areas, offering new opportunities for sustainable city development. Indeed, due to climate changes, population growth and the already high urbanization, resources like energy and water are becoming scarcer and scarcer, as their cost keeps rising up. In this sense, promoting UA up-cycling projects in urban areas might be fundamental to recover these finite resources while fostering a new typology of green architecture. Furthermore, today more than ever, shifting towards new circular and sustainable food systems is crucial as industrial agriculture is the most resource-consuming human activity on this planet, with 70% of freshwater usage, 50% of global habitable land usage, and 26% of global greenhouse emissions. In this regard, modern off-soil agro technologies represent a big opportunity to bring part of the agricultural production right within the cities' boundaries, reducing soil, water, and energy consumption, creating metabolic flows of resources between the urban built environment and the food production systems. In this scenario, food production should be considered a full-fledged new paradigm of green urban planning.

Starting from these considerations, the aim of this research is to answer the question of how we can re-use residential buildings' waste streams as a resource for urban food production, specifically focusing on water and nutrients recovery from domestic wastewater. As a result, this thesis wants to propose green building design strategies that will facilitate the construction of a metabolic architecture through the integration of off-soil hydroponic systems as final domestic wastewater treatment.

Introduction

This thesis is born with the intent to connect two worlds: the architectonic one and the agronomical one. The cross-contamination of these two disciplines was fundamental to understand and propose models of Urban Agriculture where agricultural knowledge is a full-fledged new paradigm for the development of new architectural constructions. In this sense, the thesis was carried out prevalently at the department of Architectural Technology of the University of Florence with the support of the department of Agro-food Sciences and Technologies (DISTAL) of the University of Bologna. Therefore, the research is collocated within two academic disciplines:

1. AREA 07 - AGRICULTURAL AND VETERINARY SCIENCES: **AGR/04 - Vegetable and ornamental crops.**

2. AREA 08 - CIVIL ENGINEERING AND ARCHITECTURE: **ICAR/12 - Architectural Technology.**

Throughout the three and a half years of the research, two tutors took turns and followed the development of the thesis: the first one was professor Marco Sala, who helped set up the research during the first year; the second one was professor Leonardo Zaffi, with the support of professor Vincenzo Legnante, who substituted professor Marco Sala as he retired on the second year of the thesis. From the University of Bologna, the contact person for this thesis was professor Francesco Orsini, who closely followed the whole development of the research.

During the period of the research, many activities were carried out to increase the candidate's knowledge on the topic of Urban Agriculture and to actively participate in international research on the topic. These activities include:

- Participation in the international competition "Can you design the ultimate greenhouse?" organized by Wageningen University & Research (WUR). The competition consisted of the retrofitting of an ex-prison tower and its repurposing in a Vertical Farm. The project was carried on with a mixed group of students and professionals both from the architectural and the agronomical world. The team was composed of architects and agronomists from both University of Florence and Bologna. The team was awarded the third prize at Wageningen and, at a later time, with the first prize at the EcoTechGreenAward 2018, in the category of best research projects.

- The organization of three consecutive "UrbanFarm Student Challenge" (from 2019 to 2021) together with professor Francesco Orsini and the Alma Mater University of Bologna (https://site.unibo.it/urban-farm/en). The competition is open to student teams from all over the world, and teams may comprise students from different universities and universities of applied sciences. Multidisciplinary student teams from the Faculties of Agriculture, Biology, Architecture, Design, Economics, Engineering, and Social Sciences, are usually invited to join the challenge and design innovative urban agriculture systems that integrate the best architectural and technological innovations for food production in urban environments. Their projects are always based on existing vacant spaces in three different cities, characterized by different peculiarities. Their design should have a strong and entrepreneurial connotation, promoting the generation of new forms of employment for disadvantaged users.

- A six-month internship at Wageningen University & Research in the department of Greenhouse Horticulture under the tutoring of dr. Cecilia Stanghellini and ir. Alexander Boedjin.

- Participation in the Horizon2020 call From Farm to Fork with a mixed consortium composed of SMEs and research institutions from Germany, Italy, Greece, Spain, and Denmark. The proposal consisted of the design of three pilot vertical farms in three climatic contexts (Patras (GR), Florence (IT), Potsdam (GE)). Results are still pending.

- Several scientific publications such as:
  - Orsini, F., Pennisi, G., D'Alessandro, A., Kratochvilova, D., Steffan, G., Paoletti, M., Sabbatini, G., D'Ostuni, M., Trombadore, A. and Gianquinto, G. (2020). Bridging interdisciplinary knowledge for sustainable urban landscapes: results from the international student competition UrbanFarm2019. Acta Hortic. 1298, 97-106 DOI: 10.17660/ActaHortic.2020.1298.15Â https://doi.org/10.17660/ActaHortic.2020.1298.15

  - Trombadore A., Paludi B., D'Ostuni M., *The energy of the green: green facades and vertical farm as dynamic envelope for resilient building,Â* Journal of Physics, Conference Series, Volume 1343, Number 1 2020.
    DOI: 10.1088/1742-6596/1343/1/012172

  - Orsini F., D'Ostuni M., Pennisi G., Paoletti M., Steffan G., D'Alessandro A., Kratochvilova D.,Â *Urban Farm 2019 - Projects for the former Zanussi area in Conegliano*, Bologna 2019 - UniBo. ISBN: 9788854970038. DOI: http://doi.org/10.6092/unibo/amsacta/6198

  - Orsini F., D'Ostuni M., Pennisi G., Paoletti M., Steffan G., D'Alessandro A., Kratochvilova D., *Urban Farm 2019 - Book Finale challenge*, Bologna 2019 - UniBo. ISBN: 9788898010936

  - Orsini F., D'Ostuni M., Pennisi G., D'Ercole R., Tamburrini A., *Urban Farm 2020 - Book Finale challenge*, Bologna 2020 - UniBo. ISSN: 2612-7660

  - D'Ostuni M. (2019), *Cities shaped by food - A new architectonic Avant-guard*, in UrbanFarm 2019 - Book Finale challenge, Bologna 2019 - UniBo pp. 60-61. ISBN: 9788898010936

  - Zaffi, L. and D'Ostuni, M. (2020) â€œMetabolic cities of the future. Between Agriculture and Architecture,Â *AGATHON | International Journal of Architecture, Art and Design*, 8(online), pp. 82-93. DOI: 10.19229/2464-9309/882020.

References

The main references for this research have been:

- Bibliographic references such as scientific papers, doctoral thesis, conference acts, EU and research institutions reports. Most scientific papers have been found through Google Scholar, by typing the researched keywords, Elsevier and Web of Science. A great help to the research was also provided by the website edeopt.WUR, the research website of Wageningen University & Research.

- National and international conferences. Most attended conferences were in Italy, in the UK, and the Netherlands.

- Interviews with international experts and practitioners of Urban Agriculture. All the interviews were conducted in English. The experts were chosen by their curriculum and their availability. Even when not directly cited in the research, the interviews with experts provided great help in framing the cognitive framework of the research.

- Dedicated websites to Urban Agriculture and Urban Farming technologies. Recently, a great number of websites concerning UA and hydroponic technologies are easily accessible on the internet. Several websites were consulted and compared with the literature review to add pieces of information that weren't found in specific scientific articles. Also, the website agritecture.com helped to find some of the selected case studies analyzed in Chapter 2.

- International and EU regulations. To better define the possibilities and limitations of UA, several EU regulations and local planning reports were studied.

General Objective and Specific Objectives of the research

The general objective of this thesis is to understand the phenomenon of Urban Agriculture in Europe, analyzing it from the architectural point of view. In particular, this research aims to identify and analyze the broad spectrum of UA applications focusing on the technological aspects of Urban Farming that could enhance the sustainable development of green buildings and districts. Recently, an increasing number of projects have started to propose the integration of food production within the architectonic design. However, it was often noticed that these projects use food production as a strategy to increase the quality of the architectonic design without really developing the interactions between the architectural and the production spaces. In this sense, this thesis wants to be a field manual for architects, planners, and municipalities that are willing to integrate advanced, off-soil food production systems in their projects. Using high-tech technologies for food production is a powerful tool to boost the design of green buildings and circular districts while implementing high-yielding local food production systems. Therefore, it is strongly believed that architects should have a deep knowledge of the agricultural components of UA when proposing designs that integrate food production in their buildings. In this context, this thesis could be read as a cognitive tool for planners, architects, and public administrations for the development of high-tech Urban Farming projects in European cities, providing a set of recommendations and an in-depth analysis of the technologies and the off-soil food production systems that must be used to achieve high-performance Urban Farming projects.

In this sense, the specific objectives of this thesis are:

1. *Propose back up tools supporting the design of integrated U.F projects in European cities:*

   - Analyze and determine the benefits of integrating advanced food production systems in buildings. This practice is commonly known as Building-integrated Agriculture (BIA). Its objective is to enhance circular flows of resources between the building and the food production system. In this regard, together with an extensive literature review, 21 case-studies were selected, analyzed and compared to extrapolate the circular strategies used in the selected projects with the objective to enhance the integration of advanced food production systems within the constructed environment.

- Develop precise guidelines to select edible crops in urban areas with regards to people's health and diets.
- Analyze the interactions between the food production systems and the built environment with the objective to maximize circular flows of resources. Due to the limited research conducted on nutrients and water recovery from domestic wastewater, the research specifically focused on domestic wastewater treatment and its reuse for agricultural purposes.

2. *Define a broad methodological approach for the design of BIA models coupled with domestic wastewater treatment and reuse:*

   - Determine the best wastewater treating technologies in order to assess their functioning and performances.
   - Assess a precise methodology that could be used to develop BIA models with regards to wastewater treatment and its reuse directly in the integrated food production system. In order to define the methodology, an applicative case study was used as a support to experiment with the analyzed technologies and assess their performances on a real-life scenario.

Considering the specific objectives listed above, it is important to make a distinction between the Specific Objective (SO) 1 and 2: the first SO was set beforehand when starting the thesis, therefore, the whole development of the cognitive framework was organized to reach this specific goal; on the other hand, the SO 2 was set on a later stage of the thesis, only once a deeper knowledge on UA practices and technologies was acquired. In this regard, The topic of water and nutrients recovery from wastewater was found particularly interesting as few publications on the matter are reported yet, and it seemed to constitute the element of major originality of this thesis.

Structure of the thesis

This thesis is divided into three parts:

1. *Part 1 - Context and Background.* In the first part of the research, it was defined the framework of Urban Agriculture and Urban Farming, focusing on the reasons why bringing agricultural practices within the city borders has been receiving increasing attention from the scientific community. Part 1 was then divided into two chapters:

   - **Chapter 1: Introduction to Urban Agriculture.** In Chapter 1 it was possible to analyze the crisis factors of the modern food system that called for a shift in the way we produce food. In this regard, UA has been recognized as a possible solution to shorten the food chain and propose fresh food for local communities in urban areas. Subsequently, it was analyzed how UA has developed through history, focusing on how food used to shape cities before the industrial revolution and how the food systems have changed since then. Finally, the first chapter focused on the benefits of integrating food into the city, and how architects are approaching the matter these days.
   - **Chapter 2: Urban Farming. Practices and technologies**. Chapter 2 follows by making a distinction between UA and Urban Farming (UF). In this scenario, UF is considered as a macro sub-type of UA that only considers crop production without taking into consideration livestock. In this sense, a brief analysis of the broad application of UF was carried out in Chapter 2, to finally focus on two sub-types of UF: Zero Acreage Farming (ZFarming), and Building-integrated agriculture (BIA). The reasons why this research focuses on these two specific subtypes of UF are justified as both practices imply a deeper connection with the architectural environment, being integrated into and on buildings. Subsequently, it was possible to proceed with the review of 21 selected case studies of ZFarming and BIA

projects to better understand the implications of integrating food production within the architectural design at different project scales. Finally, the analysis of the case studies was crucial to extrapolate the food production technologies used in the selected projects, as well as to analyze how architects have used food production to enhance the circularity and sustainability in their design.

Outcomes
Define the applications of Urban Farming that can be used by architects to implement the sustainable and circular design of new green buildings and districts. Assess the most commonly used food production systems and understand how the integration of these systems in and on buildings can implement a local circular economy of food and resources.

Methodology
The methodology used to carry out the first part prevalently consisted of an extensive literature review of scientific papers and specific monographic books on the topic of Urban Agriculture and Urban Farming. Furthermore, several interviews with experts in the field were carried out to better framing the context in which UA practitioners operate.
Concerning the analysis of the selected case studies, they were reported and collected in specific sheets characterized by a rigid structure. The rigid structure of the sheets helped with the comparison of different projects at different scales and was specifically developed to study the used food production technologies and extrapolate the circular strategies that stand behind the selected projects. The sheets were filled by retrieving information online from architectural magazines, architects' websites, and published literature. To better understand the implications of some projects, it was possible to go and visit some of the selected case studies (especially in Europe) that were considered within reach.

2. *Part 2 - Design inputs for the integration of advanced Urban Farming projects in architecture*. The second part of the research consisted of finding the inputs for the development of BIA and ZFarming projects in cities. Part 2 mostly focused on the technologies required to operate advanced off-soil Urban Farming systems and on the benefits and limitations that the application of these technologies may provide. Part 2 is divided into two chapters:

- **Chapter 3: Advanced hydroponic technologies.** The first part of the third chapter is a review of the most common hydroponic technologies, focusing on their functioning and their application. Based on the analysis of the best-available technologies the first part of this chapter is concluded with the development of specific strategies for the integration of these technologies within the architectural environment. Following the analysis of the hydroponics technologies, it was possible to determine the best geographic and climatic scenario in which these technologies are best applied. In this sense, it was found that the Center-Northern European context represents the most suitable scenario for the integration of advanced off-soil hydroponic technologies in the built environment. Therefore, two urban plans of two major cities like Amsterdam and London were analyzed to understand how and why these municipalities are already integrating food production within their borders. What emerged is that cities see UF as a possible solution to implement a local circular economy while providing the local communities with fresh produce. In this regard, this chapter is concluded with an analysis of the benefits concerning cities' circular development of integrating advanced food production in cities.
- **Chapter 4: Beyond food production: closing water and nutrients loop in green buildings through an integrated hydroponic wastewater treatment plant.** Following the concluding considerations of Chapter 3, Chapter 4 started analyzing the potential impacts of BIA with regards to the development of a local circular economy. Considering that the analyzed plans of Amsterdam and London highly focused on the importance of UF as a way to recover waste in urban areas, and the reported urgency in reducing the consumption of phosphate

and nitrate in agriculture, Chapter 4 focused exclusively on how to recover water and nutrients from domestic wastewater. To better understand wastewater treatment technologies and how to use treated wastewater as a nutrient solution for the integrated hydroponic systems, the whole Chapter 4 was developed during the internship period at Wageningen University & Research. The results from Chapter 4 demonstrated that domestic wastewater, especially urine and greywater, can be safely used as a nutrient solution for integrated hydroponic systems. To reach this conclusion, several case studies and scientific papers were reviewed and discussed together with the research team at Wageningen.

Outcomes
Define the best available technologies for hydroponic food production and assess the context in which they can be better exploited by their integration in the built environment. Target wastewater treatment and reuse as nutrient solution as the specific objective of the integrated hydroponic systems to maximize resource recovery in BIA projects. Review the best available technologies to recover water and nutrients from domestic wastewater in dense urban areas and assess their functioning as well as their advantages and limitations.

Methodology
The methodology used to carry out Part 2 relied mostly on the literature review. However, several visits to the greenhouses in Bleiswijk (NL) and in Bologna (IT) were carried on to properly understand the functioning of the several hydroponic and aquaponic systems. Furthermore, the participation in the Novel Farm fair in Pordenone and the GrowTech in Amsterdam was an important occasion to meet with entrepreneurs and innovators in the field of hydroponics, which help to understand and reviewing the best available technologies reported in Chapter 3. Concerning Chapter 4, it was developed at Wageningen in the framework of the GEOFOOD project, together with Ir. Alexander Boedjin and dr. Cecilia Stanghellini. Their contribution to the research was crucial to address the specific goal of recovering wastewater and reusing it as a nutrient solution in the hydroponic system. However, the sudden Corona Virus pandemic has highly delayed the development of Chapter 4, as it suddenly became impossible to meet and share pieces of information with the whole research group as happened in the first two months of my permanence in Wageningen. Finally, an important turning point in the development of Chapter 4 was the direct contact with the director of the VUNA project in Switzerland, Bastian Etter, and the scientist that carried on the VUNA experiments in South Africa, Shirly Tentile.

3. *Part 3 - Assessing the methodology for the design of Building-integrated agriculture models incorporated with wastewater treatment systems coupled with hydroponics.* Finally, Part 3 of this thesis can be considered the prepositive phase of the research, where all the inputs coming from the previous chapters converge to develop a broad methodology for the design of BIA models integrated with domestic wastewater treatment. Part 3 is composed of one chapter only:

- **Chapter 5: Developing a methodological approach for the complete recovery of water and nutrients in Building-integrated agriculture projects.** The objective of Chapter 5 is to define a broad methodology for the development of BIA models with integrated wastewater treatment by applying all the inputs coming from the previous parts to an applicative case study in Amsterdam. Selecting a project area was crucial to acquire a broader range of inputs such as the number of inhabitants, the desired urban density, and the characteristics of the buildings. The selected area is then just a canvas where to assess the feasibility of recovering domestic wastewater from the buildings and see what happens when is used as a nutrient solution for the integrated hydroponic systems. This Chapter proposes two different methodological approaches to the design of BIA models. The first one was developed at the beginning of the chapter and was used to calculate the amount of nutrients and water recovered by the system and to assess its feasibility. The second one was reported as the conclusion of the chapter, rethinking the first proposed methodology and represent a more fluid methodological approach that is more adaptable to different locations and contexts. However, what emerged from Chapter 5, is that integrating wastewater treatment technologies in BIA projects in highly dense urban areas can contribute to saving a high amount of water and nutrients while providing enough food to satisfy the demand for fruit and vegetables of the local community. The whole chapter can be then seen as a set of operational guidelines to correctly carry out BIA projects with integrated wastewater treatment.

Outcomes
Define a methodology that could be used by planners and architects to develop BIA projects incorporated with wastewater treatment and reuse as irrigation water in the integrated hydroponic systems. Determine the crops that can be cultivated in dense urban areas based on local dietary patterns to encourage citizens' healthy diets. Provide architects and planners with a simple equation that can easily calculate the amount of space needed for food production, assessing whether or not it is feasible to produce the selected crops in dense urban environments. Demonstrate the feasibility of using treated wastewater as a nutrient solution for the hydroponic system.

Methodology
The methodology used in Part 3 follows the principle of the Research by Design, using an applicative case study to assess the feasibility of the given hypothesis. In this sense, the project was carried out in four steps, according to the methodological approach proposed at the beginning of the chapter. The four steps were thought to consecutively determine: i) the crops to be produced in dense urban areas; ii) the food production spaces required to produce the selected crops; iii) the characteristics of the domestic wastewater of the given location; iv) the feasibility of using treated wastewater as a nutrient solution for the hydroponic system. The proposed methodology, however rigid tightly structured, proved to be a good starting point to retrieve all the data needed to assess the feasibility of the system and to calculate the amount of nutrients and water recovered. In this sense, the steps described in the proposed methodology can be a practical tool for planners and municipalities to properly assess the potential advantages and disadvantages of coupling wastewater treatment with the hydroponic system in the development of BIA models. However, for the proper design of BIA models by architects and planners, at the end of Chapter 5, it was proposed a different methodology, more rapid and fluid, that allows practitioners easily adjust their model to possible changes in the design process.

Future development of the research

The future development of the research, as well as the conclusion of this thesis, are reported in the final pages of this document in the section "Summary and final conclusions".

Abbreviations

BIA	Building Integrated Agriculture
BOD	Biochemical Oxygen Demand
BW	Black Water
CAP	Common Agricultural Policy
CEA	Controlled Environment Agriculture
CF	Circular Feature
CHFM	Commercial Hydroponic Fertilizer Mix
COD	Chemical Oxygen Demand
DEWATS	Decentralized Wastewater Treatment Plant
DFT	Deep Flow Technique
DSS	Decision Support System
EC	Electrical Conductivity
EPRS	European Parliament Research Service
ET	Evapotranspiration
EU	European Union
FAO	Food and Agriculture Organization
FBDGs	Food Based Dietary Guidelines
FRP	Filterable Reactive Phoshporus
GDP	Gross Domestic Product
GFA	Gross Floor Area
GHG	Greenhouse gases
GMO	Genetically Modified Organism
GW	Grey Water
HLR	Hydraulic Loading Rater
HRT	Hydraulic Retention Time
HVAC	Heating Ventilation Air Conditioning
ICTA	Institute of Environmental Science and Technology
IPCC	Intergovernmental Panel for Climate Change
IPM	Integrated Pest Management
iRTG	Integrated Rooftop Greenhouse

KR	Kitchen Refuse
MBBR	Moving Bed Biofilm Reactor
NBS	Nature Based Solutions
NFT	Nutrient Film Technique
NGO	Non Governative Organization
NUC	Nitrified Urine Concentration
OLR	Organic Loading Rate
OM	Organic Matter
PFAL	Plant Factory with Artificial Lighting
PGR	Plant Grow Rate
PLN	Plant Leaf Number
PV	Photovoltaic
RA	Rural Agriculture
RAS	Recirculating Aquaculture System
RCC	Rapid Climate Change
SDGs	Sustainable Development Goals
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solid
UA	Urban Agricolture
UF	Urban Farming
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VF	Vertical Farming
VUNA	Valorization of Urine Nutrients for Africa)
WHO	World Health Organization
WUR	Wageningen University and Research
ZFarming	Zero Acreage Farming

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PART 1: Context & Background

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Preface

Agriculture has always been the primary sustaining source for human living. Since the very beginning of civilization, the Homo Sapiens had to struggle with the natural environment to procure food, and finally ceased to be a nomad species when it discovered how to cultivate the land. Agriculture stands at the very beginning of urban environment and conditioned where and how cities were build for thousands of years.

As population grew, together with the human ability to submit the land to its will through scientific progress, Agriculture practices changed, and were able to feed an increasing number of people. Not long after the Second World War, a huge amount of chemicals, like nitrate, where converted into cheap fertilizer leading the way for the first Green Revolution which dramatically increased the production of food, opening up for a new industrial era of Agriculture.

In recent years, **we have gone from questioning our capacity to produce enough food to questioning the way we produce it** [1]: our food system's ecological footprint is not sustainable, and it is endangering the biodiversity of local ecosystems. More than 75 billion tons of fertile soils are lost every year due to desertification, soil erosion and soil degradation. We reached the paradox where the way we produce food now in an actual threat to our ability of producing food at all in the next future.

The way we produce food in not the only threat that our food system has and will have to face. Global crisis factors such as Rapid Climate Change (of which industrialized agriculture is one of the main contributors), the increasing population and urbanization trends, together with the progressive abandonment of rural areas in the developing regions of the world, forced us to rethink our global food strategies and pushed the international scientific community to find alternatives and complementary solutions to reach Food Security goals[1] in an already overcrowded world.

In this scenario, it is not difficult to understand why in the past 20 years there has been a growing interest in Urban Agriculture and even though the concept is not new, recently, a board range of research publications have become available on the subject [2]. The always growing demand of food in great urban areas makes alimentation one of the greatest issue to be addressed to. With this regard, city authorities, planners, economists, environmentalists as well as individual citizens are becoming increasingly involved in this subject area.

As reviewed in recent literature and as it will be largely discussed in this research, Urban Agriculture have a board range of applications, and takes many forms often very different from each other. Nevertheless it is possible to retrace common definitions by which UA is defined as "*..the growing, processing and distribution of food or livestock* ***within and around urban centers*** *with the goal of generating income*" [3]. Another commonly accepted definition is that UA is *"the production of food and non-food plants, as well as husbandry, in urban and peri urban areas"* [4].

Besides its capacity to produce and distribute food in urban areas, it is possible to explain Urban Agriculture's growing interest as it is considered to be a source of significant environmental, social and health-related benefits as well as economic development opportunities. Each of these has been well documented in the research literature. Nonetheless, the application of UA projects within cities' boundaries faces a number of challenges such as a diffuse skepticism from the local population, barriers to cooperation with more traditional farmers, lack of investments or difficulties in making or maintaining profits. Thus, it is important that all the actors involved in the developing of UA projects, from planners to agronomists, from architects to engineers, work together to overcome those challenges.

This research will address those aspects of Urban Agriculture that, through a technological approach, might enhance the implementation of green architecture improving circular flows throughout buildings and urban districts in a center-northern European scenario.

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[1] Related to SDG 2: Zero Hunger, Food Security definition is "Ensuring that all people at all times have both physical and economic access to the basic food that they need" (FAO, 1983).

Chapter 1: Introduction to Urban Agriculture

Urban Agriculture as a new paradigm to feed the world

As world's population grow and urbanization, which has brought half of the world population living in the cities, appears to be irreversible, the number of megalopolis is constantly increasing. The always growing demand of food in great urban areas makes alimentation one of the biggest challenges caused by the uncontrolled development of cities.

Recently, a combination of crisis factors like industrialized agriculture and the need to change the global food chain, together with worldwide issues like urbanization and rural migration brought the debate over topic such as food security and safety to the attention of the scientific community.

To this concern, a possible solution that emerged in literature, and that is now widely shared within the scientific community, is to bring agricultural surfaces from the countryside to great urban areas. Urban Agriculture emerged as a solution not only because it expands crops surfaces taking back urban vacant spaces, but also, because it can address to some of the most pressing challenges our food system is facing. To understand these challenges and how Urban Agriculture can help overcoming them, it is important to know where the flaws in our agro-system lie.

This research identified four major crisis factors of contemporary food system:

1. Industrialized Agriculture
2. Rapid Climate Change
3. Urbanization, population growth and rural areas abandonment
4. Global food chain & Food Waste

1 Agro-system crisis factors:

1.1 Industrialized Agriculture

In 1974, during the World Food Conference in Rome [5], US' Secretary General Henry Kissinger promised to end hunger in the next decade. Following to that declaration, the first Green Revolution was introduced with an enormous international campaign to spread fertilizers and pesticides to farmers all over the world. Food availability increased of a 12% per capita [1] but despite that, after two decades from the introduction of the Green Revolution, the number of people suffering from severe hunger rose from 650 to more than 800 millions, and during the food price crisis of 2008 and 2011, hunger reached the pick of 1.2 billion people. In 2015 the United Nations declared that their projections indicate a drop in the raising curve of undernourished people in the developing regions [6], but just two years later, a report from the FAO stated that "*after a prolonged decline, this recent increase could signal a reversal of trends. The food security situation has worsened in particular in parts of sub-Saharan Africa, South-Eastern Asia and Western Asia, and deteriorations have been observed most notably in situations of conflict and conflict combined with droughts or floods*" [7], and that number or chronically undernourished people has increased of around 40 million in two years.

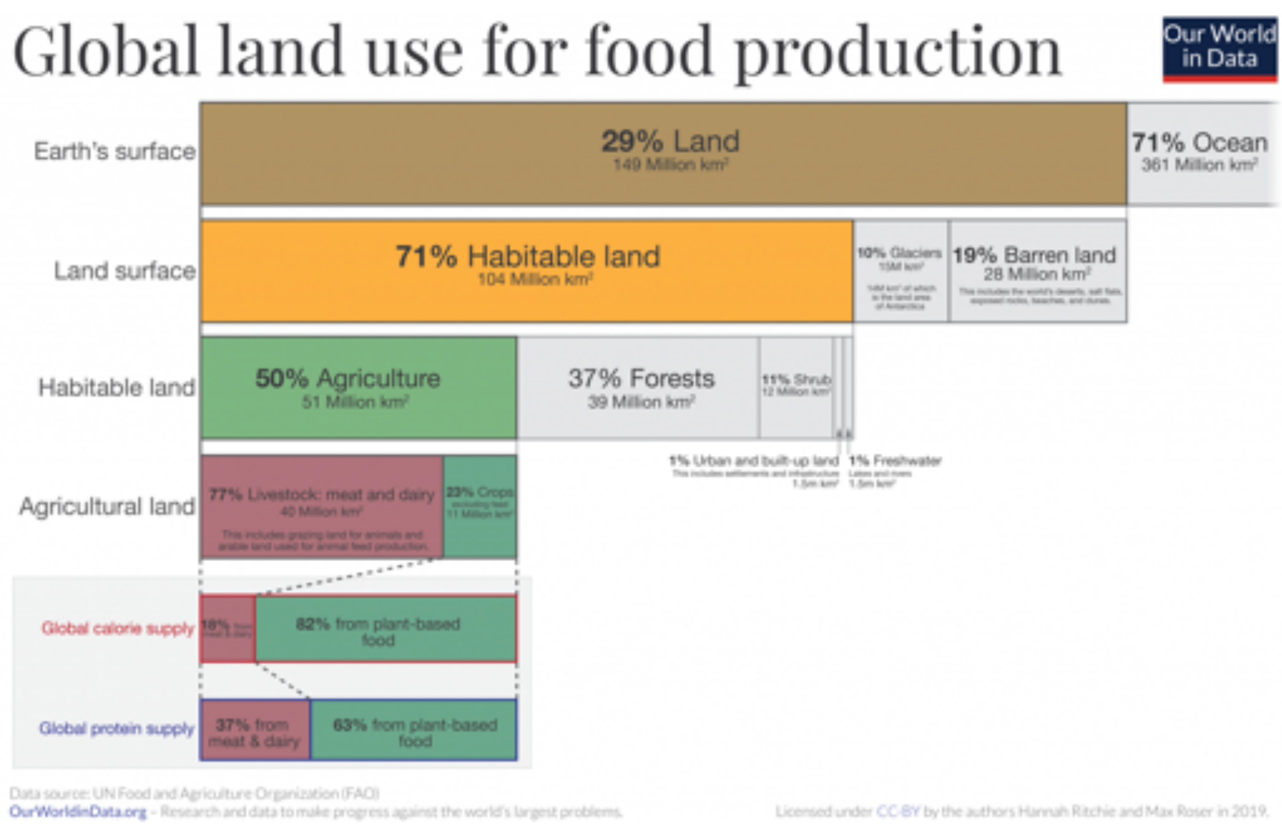
In 2009 a FAO study [8] demonstrated that the world produces more than 150% food than its food demand, and that due to industrial agriculture we already produce enough for more than 10 billion people, roughly the number of people who will leave on the planet in 2050 according to UN prospects. In the past 40 decades food production grew faster than the rate of population growth, nonetheless, this was not sufficient to end, or even dramatically reduce hunger. For this reason, it is now diffuse in the scientific community that our food system is living a crisis of over-production [9], suffering an enormous amount of food wastes, severely impacting on our planet's ecosystem: industrial agriculture, other than failed in reducing hunger, is dramatically changing soils production capacity and directly contributing to climate change. If we keep producing with the current agro-system, it has been estimated that by 2050 "*the world food demand will surge, and it is projected that food production will increase by 70 percent in the world and by 100 percent in the developing countries. Yet both land and water resources, the basis of our food production, are* *finite and already under heavy stress, and future agricultural production will need to be more productive and more sustainable at the same time*" [10]. Ecologically, industrial agriculture is creating vast, monocultural desert, which makes impossible for farmers to cultivate the land without the use of great amounts of synthetic herbicides and pesticides, causing the desertification of agricultural soils, the depletion and pollution of important water resources and the loss of biodiversity. The environmental effects of these practices are devastating, and it is possible to see their impact in the four ecological pillars of the food system: soil, water, biodiversity, climate.

Soil

The expansion of agriculture has been one of humanity's largest impacts on the environment. Through technology advances and the use of synthetic fertilizers, crop yields have increased significantly in recent decades, meaning a lot of land has been spared from agricultural production: globally, to produce the same amount of crops as in 1961, only 30% of the equivalent farmland is required [1].

In fact, after World War II ended, huge amounts of nitrates used to fabricate explosives were employed in the making of cheap synthetic fertilizers. In the 70s, when most of industrialized countries were no longer able to buy all the synthetic fertilizers and farm machinery, the Green Revolution exported them in the developing world in order to increase food production. The use of synthetic fertilizers like nitrogen, phosphorus and potassium eliminated the use of animal manure as fertilizer causing the loss in agriculture of its organic matter. Soon, plants were no longer able to fight the damages caused by pest and diseases without the use of synthetic fertilizers. It is estimated that every year agriculture is losing about 75 billion tons of crops soil [11].

Fig. 1 - Global land use for food production



Source: OurWorldInData.org

Water
"*On average, agriculture accounts for 70 percent of global freshwater withdrawals. In the last 30 years, food production has increased by more than 100 percent*". With the growing population, water demand is expected to increase. Following FAO projects, it is estimated that "*irrigated food production will increase by more than 50 percent by 2050, but the amount of water withdrawn by agriculture can increase by only 10 percent, provided that irrigation practices are improved and yields increase"* [12].

Over the 1 400 million cubic km of water estimated in the world, only 0.003% of this vast amount, (about 45 000 cubic km), are "fresh water resources" that could be used for drinking, hygiene, agriculture and industry, and not all of it is accessible due to geographical limitations. As climate change increases, severe droughts pushed farmers to dig always deeper wells in the ground to find water sources that could irrigate their crops. Those sources are so remote that it is impossible for rainfall to recharge them anywhere in the next future.

Furthermore, agricultural runoff is the main responsible for aquatic 'dead zones'[2]. The high amounts of nitrogen and phosphorus present in common pesticides and herbicides flow with the water back into rivers, lakes and oceans, favoring algal blooms. Once dead, algae decomposition suck up all the oxygen in the water causing the death, or migration, of all aquatic life. It does not come as a surprise, that since the second half of the XX century, in conjunction with the use of chemical fertilizers, dead zones around the world have expanded over 1000% [1].

Industrial agriculture is contaminating water supplies, making the whole agricultural system vulnerable to the uncertainties caused by Rapid Climate Change (RCC). Possible solutions to overcome the problem might be the return to organic agriculture where organic matter comes back to the soil, and the use of soil-less cultivations which can control the amount of water used for irrigation and that can reduce the use of chemical fertilizers.

Biodiversity
Agriculture is a major use of land. Half of the world's habitable land is used for agriculture. The extensive land use has a major impact on the earth's environment as it reduces wilderness and threatens biodiversity.

Industrial agriculture production has caused a massive "Great Insect Die-Off" [1]: a study from the University of Nijmegen [14] reported that in Germany, there has been a decline of 75% of flying insects since 1990, mostly due to the use of pesticides. The death of so many insects will threaten lives of birds fish and mammals.

Eric Holt-Giménez [1] stated that since the beginning of the Green Revolution over 70% of the world's agro-biodiversity has been lost, explaining that local diversity is gone forever due to the use of just few commodity crops which replaced the the traditional ones who became indigenous in hundreds of years of natural selection. The use of modified sterile crops is the cause for the loss of soils' resilience, and, all year-round monocultural crops are impoverishing the biodiversity of the grounds.

Climate change
Based on data from the meta-analysis made by Joseph Poore and Thomas Nemecek (2018), published in *Science* – it is possible to summarizes food's share of total emissions and breaks it down by source. Food is responsible for approximately 26% of global GHG emissions [15].

There are four key elements to consider when trying to quantify food GHG emissions:

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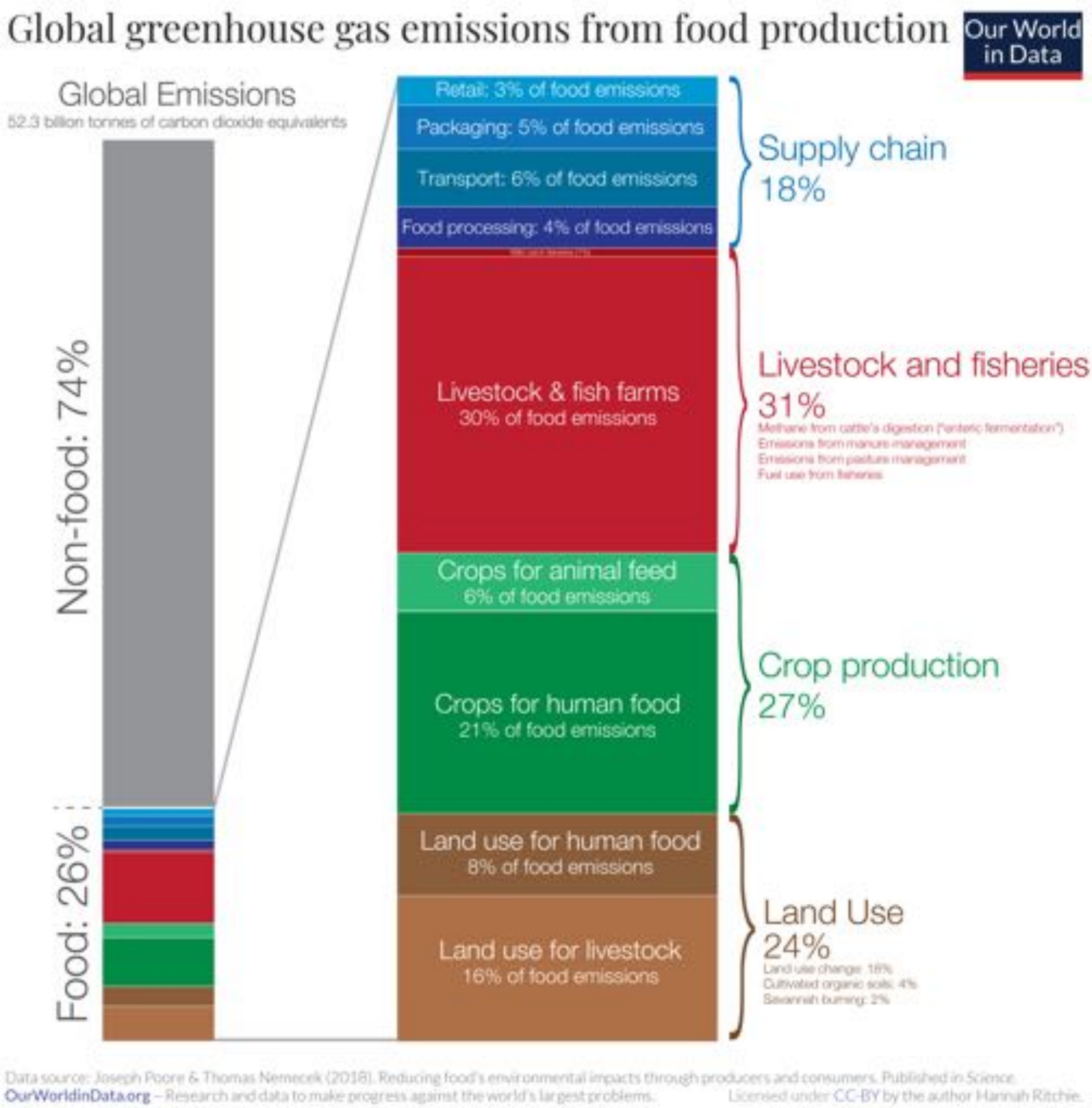
[2] "'Dead zone' is a more common term for hypoxia, which refers to a reduced level of oxygen in the water. Less oxygen dissolved in the water is often referred to as a "dead zone" because most marine life either dies, or, if they are mobile such as fish, leave the area. Habitats that would normally be teeming with life become, essentially, biological deserts."
National Oceanic and Atmospheric Administration U.S. Department of Commerce 'What is a dead zone?' Updated March 2020, https://oceanservice.noaa.gov/facts/deadzone.html

Livestock & fisheries account for 31% of food emissions. Livestock practices are intended as animals raised for meat, dairy, eggs and seafood production.

Crop production accounts for 27% of food emissions. 21% of food's emissions comes from crop production for direct human consumption, and 6% comes from the production of animal feed. They are the direct emissions which result from agricultural production – this includes elements such as the release of nitrous oxide from the application of fertilizers and manure; methane emissions from rice production; and carbon dioxide from agricultural machinery.

Land use accounts for 24% of food emissions. Twice as many emissions result from land use for livestock (16%) as for crops for human consumption (8%). Agricultural expansion results in the conversion of forests, grasslands and other carbon 'sinks' into cropland or pasture resulting in carbon dioxide emissions. 'Land use' parameter is the sum of land use change, savannah burning and organic soil cultivation (plowing and overturning of soils). A study from Sam Lawson [16] estimated that 70% of deforestation is caused by the need of new arable farmland for commercial crops.

Fig. 2 - Global greenhouses gas emissions from food production



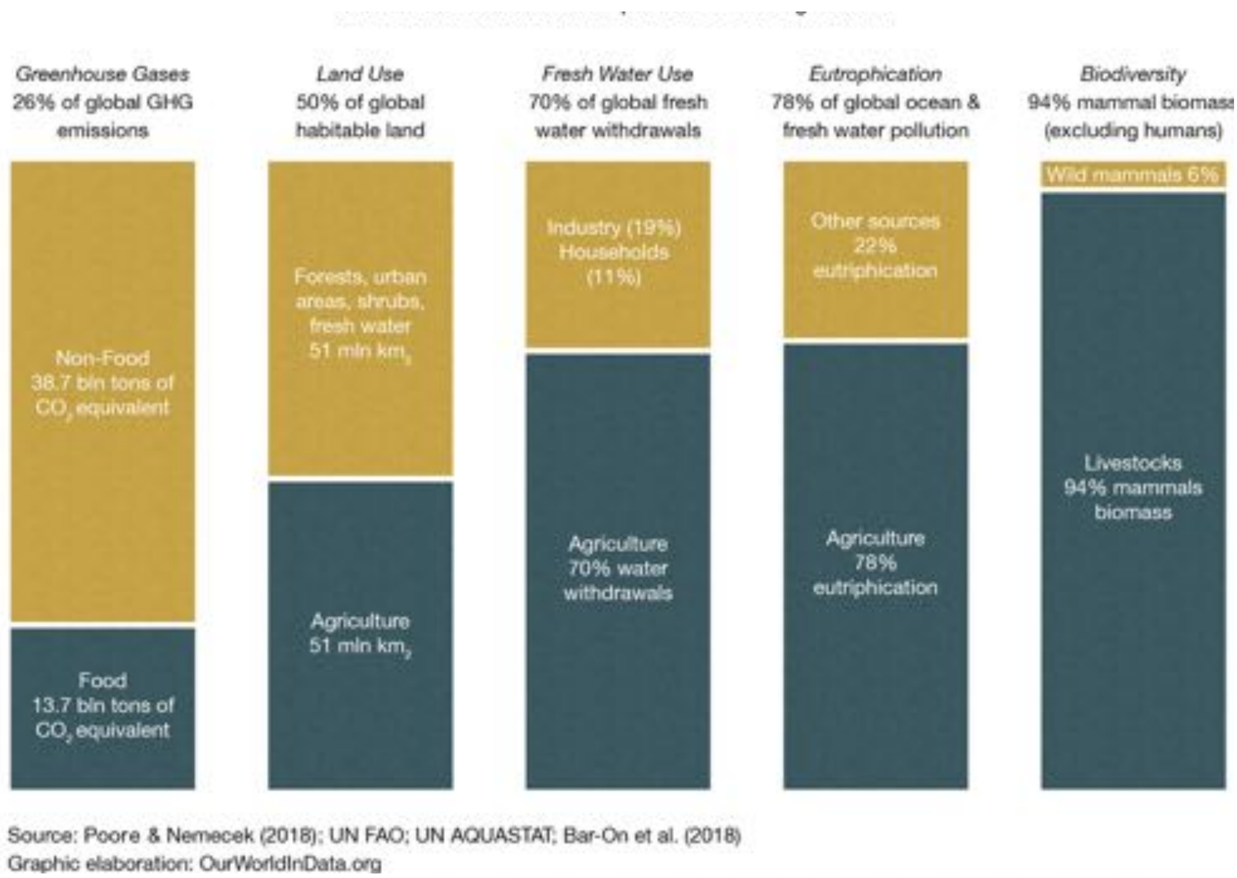
Supply chains account for 18% of food emissions. Food processing (converting produce from the farm into final products), transport, packaging and retail all require energy and resource inputs. Many assume that eating local is key to a low-carbon diet, however, transport emissions are often a very small percentage of food's total emissions – only 6% globally. Whilst supply chain emissions may seem high, at 18%, it's essential for *reducing* emissions by preventing food waste.

Based on this data, it is possible to conclude that the high impact of agriculture on GHGs emissions is not only caused by the use huge amount of chemicals and fossil fuels, but also from its ecological footprint that causes the loss of vegetation, forests and soil organic matter.

It is possible to see the flaws of this food system if we consider that 24% of all our food goes to waste, 35% is for animal food and 3% goes to biofuels [1].

In this scenario, it is imperative we change the way we produce food. Reducing food waste, together with implementing soils resilience and improving the use of water resources is a key factor for future production. Increasing the amount of food that we produce to feed a growing population should then not be the only answer.

Fig. 3 - Environmental impacts of food and agriculture



1.2 Rapid Climate Change (RCC)

RCC is one of the biggest challenge the world is facing right now. In recent years it has become clear that our whole capitalistic system is putting in jeopardy the planet's future, and human actions are literally modifying terrestrial landscape. In this scenario, it is believed that climate change will affect our ability to farm [17]. Thus, it is likely that climate variability and change will exacerbate food insecurity in areas currently vulnerable to hunger and undernutrition [18].

"The impacts of climate change will have many effects on the global food equation, both for supply and demand, and on food systems at local levels where small farm communities often depend on local and their own production. Climate change affects vulnerability to food insecurity in the first instance through its biophysical effects on crop, livestock, and farming system productivity.

Changes in temperature and precipitation means and increased variability translate into changes in average levels and variability in food production, with follow-on effects on income for food producers and food affordability for net purchasers in rural areas and for urban consumers. Expected increases in climate variability will result in increased variability in agricultural production leading to more price and income fluctuations. Management of risk by all participants in the food system, from individuals and households to nations, will be ever more important […] Effects will be felt directly in rural areas and indirectly in urban areas via higher prices and more variability." [19]

Using regression analysis of historical data, a research by David Lobell (Lobell, et al., 2011) [20] strongly suggests that observed rising temperatures in the second half of the 20th century and early years of the 21st century, and accompanying changes in precipitation, have already had demonstrable and varying effects on agriculture across the globe: global average temperatures have risen by roughly 0.13°C per decade since 1950 and an even faster pace of roughly 0.2°C per decade of global warming is expected over the next two to three decades [21]. The study compared data sets on crop production, crop locations, growing seasons, and monthly temperature (T) and precipitation (P) with a panel analysis of four crops (maize, wheat, rice, and soybeans) for all countries in the world. The four crops together constitute roughly 75% of the average calories consumed in worldwide diets. From the combination of these factors with the five selected crops it was possible to develop a database of yield response models to evaluate the impact of these recent climate trends on major crop yields at the country scale for the period 1980–2008. According to these findings, there are dramatic regional differences in the recent past (1980-2008) in terms of change in growing season temperature: small changes are found in North America whereas large increases are found in other parts of the world, particularly Europe and China.

Rapidly increasing GHG emissions, especially in developing countries, combined with growing evidence of negative climate change effects on agriculture, the likelihood of nonlinear effects of temperature on yields, and hints of the added burden of more frequent extreme weather events suggest an extremely serious challenge for sustainable food security.

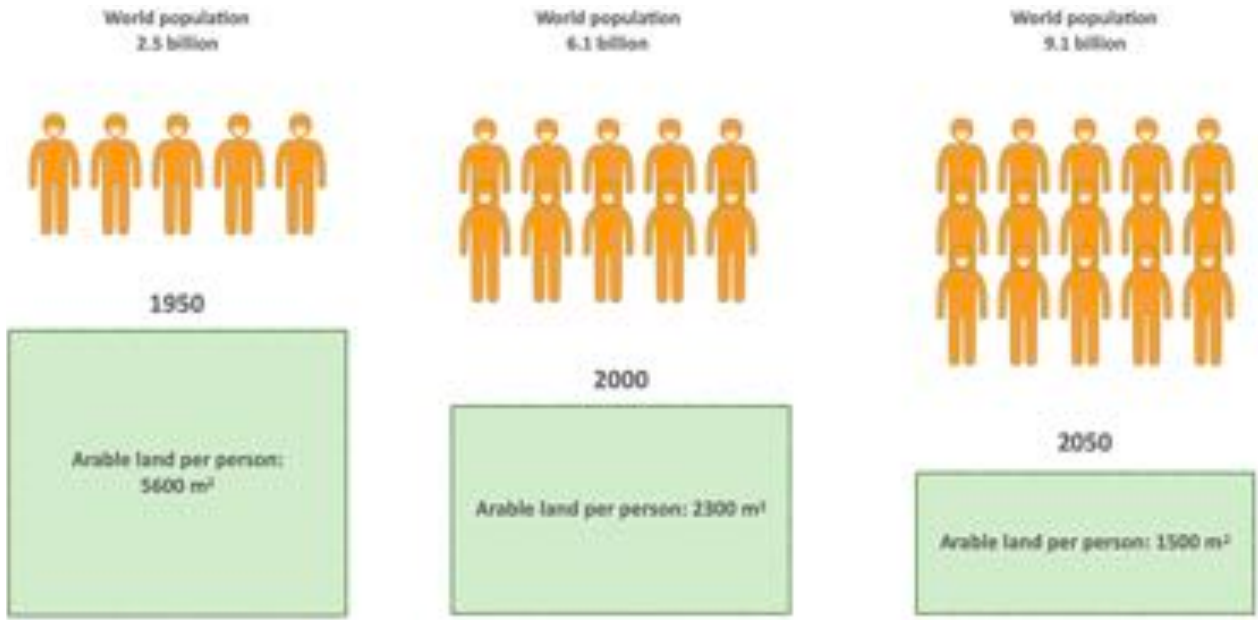
Vulnerability of food and nutrition security to climate change is a function of all the driving factors mentioned above. Biophysical changes from climate change affect food availability through supply impacts (e.g., changes in average yields and increases in variability) and the resulting challenges to livelihoods of producers. Climate change also has important implications for food distribution and access as they depend on climate-resilient road infrastructure, markets and other social and economic institutions. In addition to these supply side effects, climate change might affect utilization (demand by consumers), not only through effects on their incomes but also consumption behavior.

Consequences for food stability could come from increased incidence of extreme events leading to more frequent temporary food shortages and stresses on resource availability and contributing to political unrest [19]. Climate change could increase the vulnerability of small farms because they are likely to have limited access to technologies to adapt to climate change because of weaknesses in the extension and credit systems. This will have to be considered in the framing of national agricultural development policies. And if these land transactions also result in conversion of forests and woodlands to agriculture, GHG emissions will worsen.

1.3 Population growth, urbanization trends and rural areas abandonment

According to the UN 2017 World Population Revision, it is estimated that in the world there will be living 8.6 billion people by 2030 and 9.8 billion people by 2050. From 2017 to 2050, it is expected that half of the world's population growth will be concentrated in just nine countries: India, Nigeria, the Democratic Republic of the Congo, Pakistan, Ethiopia, the United Republic of Tanzania, the United States of America, Uganda and Indonesia (ordered by their expected contribution to total growth). [22].

Fig 4: Arable Land for Person 1950 – 2050



Source: Own work based on *Perfetti, P., 2010. The New Millennium Risk Game Explodes: the Capture of Territories has just Started. Energia, Ambiente e innovazione 2. Proctor, W., Drechsler, M., 2006. Deliberative multi-criteria evaluation. Environ. Plan 24, 169-190*

As of today, 55% of the world's population lives in urban areas according to the UN 2018 Urbanization Revision. This proportion it is expected to increase to 68% by 2050. Projections show that urbanization, the gradual shift in residence of the human population from rural to urban areas, combined with the overall growth of the world's population could add another 2.5 billion people to urban areas by 2050, with close to 90% of this increase taking place in Asia and Africa [23].

Migration flows from rural to urban areas, are historically driven by economic development. Today, 97% of the global GDP is generated by industries and services, and 65% of the work active population is employed in industries and services which are concentrated in urban areas. A commentary by Stefano Miccoli from 2016 notes that as the larger urban areas and income of their residents grow, the demand for food also grows. As a consequence, the agro-system "as-it-is" will have to respond to this increased demand by increasing production from between 70 % to 100 % of current volume by 2050 [10]. The same commentary points out that it is expected that the area of arable land will not be able to grow by more than 12% compared to today [24].

Urban expansion will inevitably cover some agricultural land while changing land values. Urban centers often expand over their nation's most productive agricultural land since most urban centers grew there precisely because of highly fertile soils. Most of the world's major cities today have been important cities for several hundred years, so they became important cities before the development of motorized transport (and later refrigeration) that reduced cities' dependence on their surroundings for food and other agricultural products [25]. As a consequence, markets are predicted to become more concentrated with urbanization, shifting diets towards more processed food. These processes could worsen climate mitigation challenges if they result in replicating the current land, energy, and GHG-emissions-intensive models of agricultural production and supply and distribution chains [19].

Climate change impacts on agriculture will affect urban areas influencing food availability and price. On the other hand, climate change impacts on urban areas will affect agriculture with possible disruptions in urban demand for agricultural produce and disruptions to the goods and services provided by urban enterprises to agriculture and to rural households [25]. In this scenario, the HLPE predicted that supporting food and nutrition security and safety for an increasing urban world requires special adaptation strategies and implementation of Urban Agriculture practices.

Historically, there has always been a link between the development of organized agriculture and the process of urbanization [26]. As an example, in the rise of urbanization during the industrial era, urban agriculture has emerged as part of a counter-movement to protect the population from social dislocation or as a form of coping strategy. In this context, the integration of food production systems in urban areas appears to be one possible solution to meet the increasing demand of food caused by the same urbanization.

1.4 Global food chain & Food Waste

Since the beginning of the first industrial revolution, cities started to break ties with their rural hinterland, which caused a reduction of cities' dependence on their surroundings for food and other agricultural products. Of course, for prosperous cities, the demand for agricultural commodities has long-since gone far beyond what is or could be produced in their surroundings. There has been an increasing separation between places of food production and those of consumption. Urban areas rely heavily on a multitude of food systems to meet their food needs and this makes them vulnerable to any crisis in the food supply chain.

Cities draw on large and complex global supply chains and have large ecological footprints, drawing on 'distant elsewhere' for food, fuel and carbon sinks[3]. The dependence of many very large concentrations of urban populations on long international supply chains for food, fuels and most intermediate and final goods makes them vulnerable to disasters in locations that supply these or buy their products, as well as to rising fuel prices [19].

Cities will have to consider the issue of food security, including strategies on how to develop more localized food production systems. European cities make great efforts to feed themselves, and environmental costs of food systems are becoming more and more unsustainable. If we take London as an example, it has been calculated that it needs 'around 150 times its own footprint just to feed itself' [26]. Energy conservation will drive us to shorten the global food chain. A solution could be to bring food production back to the city: "*cities have resources like land, water, labor and a ready-made market for food production. It actually makes a lot of sense to shorten our food chain by growing food right in the cities where we 'co-producers' live*" [27].

In this scenario, where places of production are completely displaced from places of consumption, it is difficult for farmer to grow the exact amount of food that will meet market demand, so they grow too much. An estimated 30 to 50% of produced food, worth 400 billion dollars a year, goes uneaten [1]. Waste in food means wasted water and energy used to produce it, and while wastes occur in a much bigger scale on a post-production phase in developing countries, food loss in the consumption phase is a prerogative of the developed world [28].

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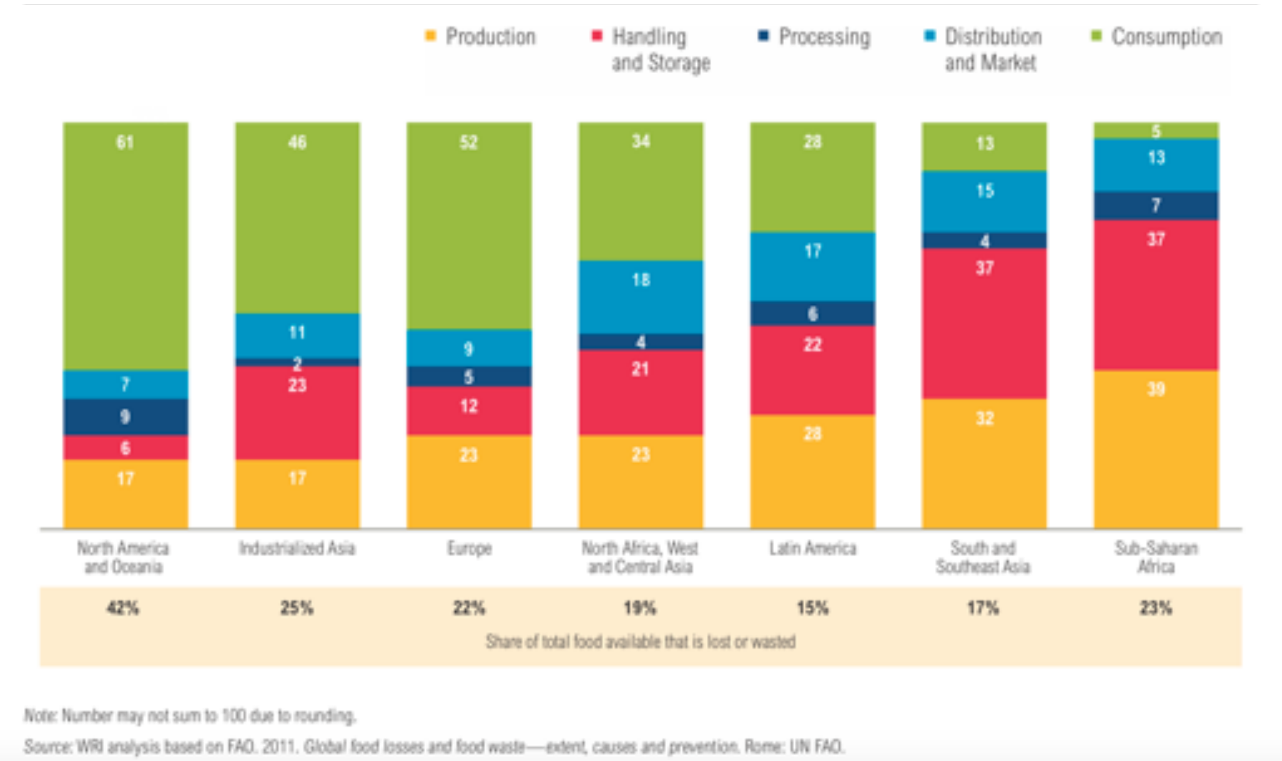
[3] A carbon sink is any natural reservoir that absorbs more carbon than it releases, and thereby lowers the concentration of CO from the atmosphere. Globally, the two most important carbon sinks are vegetation and the ocean. Public awareness of the significance of CO_2 sinks has grown since passage of the Kyoto Protocol.

Supermarkets regularly buy in stock 50 to 100% more food that they put on their shelves, that no customer can possibly buy. Challenges now lie both in the way supermarkets apply their business models and the way we produce food: produce often is not even harvested because of aesthetic imperfections, sometimes low market prices due to an exceeding offer of produce make it uneconomical to harvest certain crops and in the industrial fisheries, up to 60% of the catch is thrown even before the it could reach the local ports [1].

Waste is endemic to capitalistic agriculture overproduction, and while it is fundamental to develop new strategies addressing what it would be possible to do with the exceeding food, the real challenge is to focus on the causes that bring to food waste: turning food waste into a commodity could not be the only solution.

Fig. 5 - Food lost or wasted by region and stage in value chain



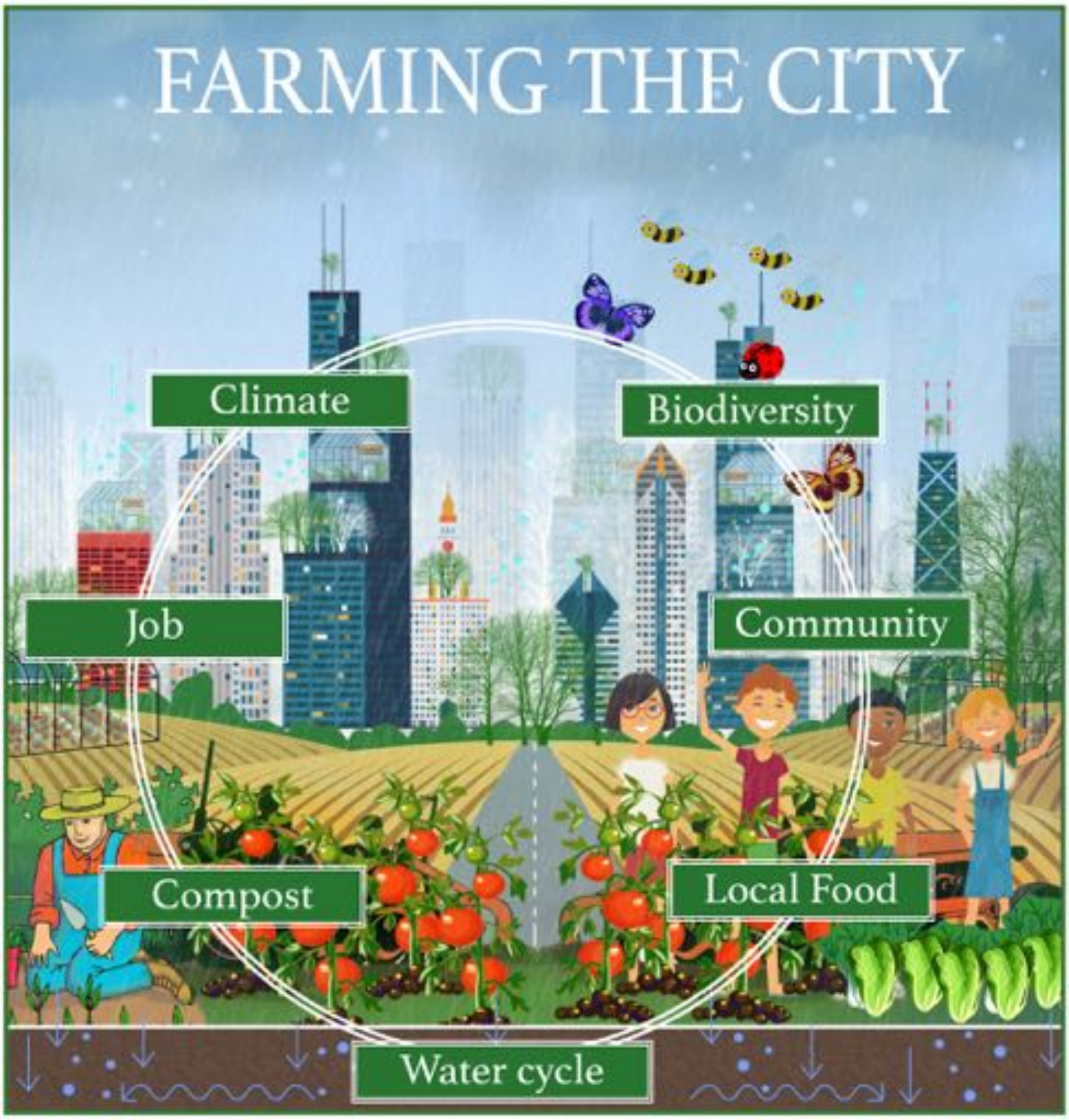
Source: *B Lipinski, C Hanson, J Lomax, L Kitinoja, R Waite. 'Reducing food loss and waste' World Resources Institute Working Paper, 2013*

1.5 The need for a paradigmatic shift in global food production

The fact that the global agricultural system is in crisis is undeniable. The crisis factors listed above show the deep contradictions of an industrialized system that live in the paradox of nurturing us while consuming the earth. Thanks to the technological advancements and their widespread use in agriculture, agricultural production more than tripled between 1960 and 2015 [29]. This caused a significant expansion in the use of land, water and other natural resources for agricultural purposes [29], followed by the constant lengthening of the food supply chain dramatically increasing the physical distance from farm to plate. Thus, the expansion of the food production system and its consecutive economic growth have had a heavy impact on the natural environment: almost one half of the forests that once covered the Earth are gone leaving the place to monocultural agriculture fields; groundwater sources are being depleted rapidly; biodiversity has been deeply eroded; agriculture CO_2 emissions rose year after year, contributing to global warming and climate change [29].

These trends area an actual threat to our possibility of producing enough food in the future for a growing population. Indeed, even small changes in the climate such as shifts in annual rainfall or seasonal precipitation patterns, can severely affect productivity. Hence, with an overcrowded future at clear sight, the core question is how modern industrialized agriculture can meet the needs of a global population that is projected to reach more than 9 billion by mid-century and may peak at more than 11 billion by the end of the century [29]. The depletion of soils together with the scarcity of land and a reduce capacity of fresh water reservoirs mark the necessity for a transition towards more sustainable and fair production systems. If it is a consensus opinion that the modern agro-business will be able to produce enough food for a growing population (it already produced food for 10 billions inhabitants [1]), it is also acknowledged that it won't be able to do so in an inclusive and sustainable manner [29]. In this scenario, several solutions have emerged that promotes a shift towards more sustainable food production practices, often complementary to each other. Strategies vary from investing in a renovated organic agriculture [9], going from commercial monocultural farms to diversified farming, to proposing the transitions towards plant-based foods as main source of proteins, with the objective to dramatically reduce the meat's consumption [30]. In this context, a strategy that is catching on is to implement food production systems within cities and large urban environment [27]. The recent fortune of this practice, known as Urban Agriculture, is connected to its capacity to target both urban and agricultural issues, proposing solutions that promote both the sustainable transition of urban food systems and new healthy urban lifestyles.

Fig. 6: Urban agriculture concept



Source: *Own work*

2 Urban Agriculture: an old practice for new solutions

As G. Keeffe said, historically, there has always been a link between the development of organized agriculture and the process of urbanization [26]. Indeed, cultivating crops in urban areas is an old practice, dating back to the beginning of civilization. In Palestine, archeologists found the rests of what was probably one of the very fist settlements in human history: Jericho. Founded around the 9.500 b.C., excavations showed that by the early 8.000 b.C. Jericho was hosting around 2-3 thousands inhabitants, organized into a proper community able to build walls and produce art. In 1.500 years, that very small settlement became a town, which could grow and develop for other 5000 years, thanks to the development of the very first agricultural techniques: complex irrigation systems and trace of grains and wheat were found in the archeological site. Eventually, even Jericho had to fall, the increasing population, greed, needs, war, drought and famine finally destroyed it after six thousands years of existence [31].

Throughout history cites have been in a codependent relationship with their countryside, and their survival strictly depended on the capacity of the land to produce food (Fig. 7): food transportation was extremely complicated and that limited the capacity for cities to expand. The very basic laws of geometry can explain that, as the larger the city grew, the smaller the size of its hinterland became with the inevitable consequence that the latter could no longer feed the former. For instance, 15th century Bologna was one of the biggest cities of its time with a population of 75.000 people, famine was most certainly much known by its inhabitants, until the black plague decimated its population partially resulting in easier food access for those that survived [31].

Fig. 7: The Allegory of Good and Bad Government - Ambrogio Lorenzetti, 1338 / 1339

Credits: *Comune di Siena*

The cultivation of plants and crops in villages and towns was an established practice during the middle age in the from of *hortus* [32]. The *hortus* pattern recurred through gardens that complete the village's general geometry and feed the local community [32]. They were usually positioned at the borders of towns, adjacent to the defensive walls, enabling food security in times of siege (Fig. 8). During the same time, horticulture was also developed in monasteries where food production and processing were established under the Rule of Saint Benedict [32]. Going ahed in time, during the Renaissance the horticultural practice assumed the form of art and urban design, creating the Italian and French gardening schools paving the way for modern landscape architecture principles [32].

Fig. 8: Historic map of Florence. P. Van der Aa, 1728

Credits: *SANDERUS, antique maps and books*
Urban hortus and gardens are clearly visible in this map and willingly highlighted with a higher saturation. From this historic map, it is possible to appreciate the location of the urban hortus, right next to the borders walls

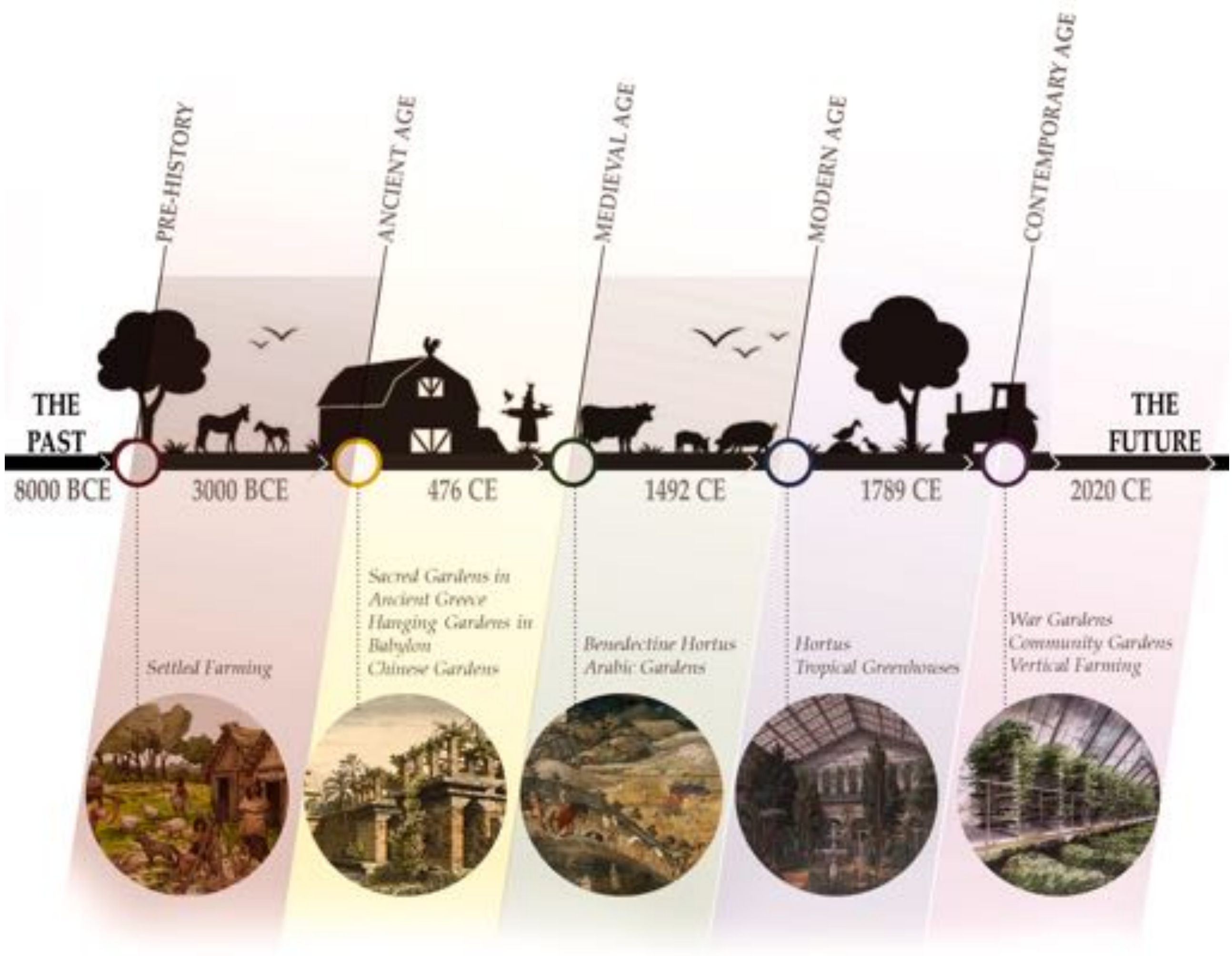
Until the 19th century food had strongly determined where and how cities were built. However, during the industrial revolution, the appearance of new infrastructures that were able to connect cities at high speed suddenly changed this paradigm: once the first railways started to be built in Europe it was clear that they represented an unprecedented opportunity to distribute food all around cities and countries. The boundaries of urban environment and rural hinterland started to fade and the city sprawl was then unstoppable. Still, some forms of urban agriculture persisted: during the industrial revolution gardens were found within the fringes of industrial towns, contributing to the food security of the migrant workers, and during the two great world wars of the 20th century war or “victory” gardens were promoted by governments to feed the urban population [33]. It is right in this period, at the beginning of the 20th century, that a first form of modern UA was developed by an English architect with regard to urban planning. In fact, just over a century ago in England occurred the first significant phenomena of great urbanization, with massive migrations from the countryside to the industrial city. During the Second Industrial Revolution, for the first time, a book called Garden Cities of Tomorrow (1902) by Ebenezer Howard theorized the return to a city in harmony with nature. In the chapter The Future of London, a sentence anticipates the current global situation of high population growth and large urbanization: «[…] There is a well-nigh universal current of opinion that a remedy for the depopulation of our country districts and for the overcrowding of our large cities is urgently needed. But though everyone recommends that a remedy should be diligently sought for, few appear to believe that such a remedy will ever be found» (Howard, 1902, p. 143). The British architect observed how the phenomena of urbanization, which brought entire families from the countryside to the city, produced both unhealthy suburbs and abandoned and unproductive countrysides [34]. According to Howard, one of the biggest mistakes of the time was considering industry and agriculture as two different elements separated by a clear demarcation line. His solution was to create smaller urban areas, surrounded by countryside near the existing city, arranged in a circle around it, interconnected and connected to the Central City by a railway system. Howard's hypothesis of resuming the old agricultural perimeter by readapting it and updating its use represents the first real project of modern urban farming and the energy and food self-sufficiency concepts make him one of the pioneers of sustainable urban development [35]. Unfortunately, albeit fascinating, Ebenezer Howard's theories did not have a good success in practice. Some New Towns were built but never became really self-sufficient, on the contrary, since they were dependent from the main cities, they ended up merging with them, determining one of the first phenomena of urban sprawl [34]. With respect to these experiences, today, it is legitimate to wonder whether it is appropriate to overturn the paradigm of the city moving into nature, maybe it should be nature itself to colonize the city in a salvific way with green spaces and agricultural areas.

In this sense, the progress of building and productive technologies opens to new possibilities. Green walls, garden roofs and even planting trees inside the buildings make this perspective increasingly easy to implement, entailing considerable environmental benefits of bio-dissipating pollution within the dense built urban fabric [36]. However, a more promising scenario for the future seems to be the implementation of green areas in the cities by planting crops and devices that also allow widespread food production. The crisis of the farming sector, climate change, and globalization of the markets impose a new reflection on the future of food consumption and this consideration cannot ignore the role of the metropolis. Today, technology allows to partially bring agriculture back to the city, with techniques that minimize the use of the land, use renewable energy and improve biodiversity within urban spaces, making this agricultural production capable of satisfying directly part of the food demand of the metropolis (Fig. 9). To this concern, architecture and agriculture are two sides of a same coin, which implementation could lead to the transformation of the cities of tomorrow. In this regard, the first architect to call for a renovated Urban Agriculture in contemporary metropolises was Yona Friedman in the late 70s of the 20th century. He affirmed 'L'agriculture dans la ville est une nécessité sociale' right on the edge of one of his suspended city schemes. The idea of integrating an agricultural production system within a megastructure was imagined by Friedman in 1979 [34]. Back when no one would have imagined it, the Franco-Hungarian architect wrote that urban farming, totally forgotten by the modern urbanism of wealthy cities, can be revived. It can take on two aspects: in wealthy cities, it can be useful for products (early produces) whose transport and storage are expensive (due to their fragility). The other aspect is linked to shortage: the food is produced in the city only for eating it [37]. Friedman's intuition started from the observation that the price of lots in the city was too high and this caused the shortage of green spaces, since the land was used for things considered most profitable. However, if a multi-storey structure had been built within these lots, 30% of the surface obtained could have been converted into private gardens and the configuration of the structure could have guaranteed to each of these new green areas enough light to grow and proliferate. In order to keep the heat in the green spaces, to keep the plants alive, these would have been – according to the vision of the Franco-Hungarian architect – covered by glass structures. Perhaps he was the first to investigate the concept of integration between greenhouse and home.

Seen in this light, modern Urban Agriculture can be considered a relatively new approach by which planners, engineers, architects and agronomists are trying to shape the cities of the future enhancing circularity, promoting more resilient urban spaces. Indeed, it is since 1990s that the scientific debate encompassing UA focused on competition for non-renewable resources (i.e., soil, water, land) and its economic viability [29]. UA is taking advantages where Rural Agriculture (RA), the primary producer of food in cities, failed to achieve urban food security. The concerns that modern practices of RA could deplete soils and that the process of land grabbing could cause a mass migration of rural populations towards urban areas, triggered UA movements all around the globe, with a growing number of researches and publications in recent years [2]. However, UA is unlikely to turn any city or most households fully self-sufficient in all of the food which they may require [39]. For this reason it is important not to consider UA as an alternative to

RA, but as a board range of complementary actions that could alleviate pressure on the traditional agro-system.

Fig. 9: Brief timeline of UA evolution throughout the millennia



Source: *Own work*

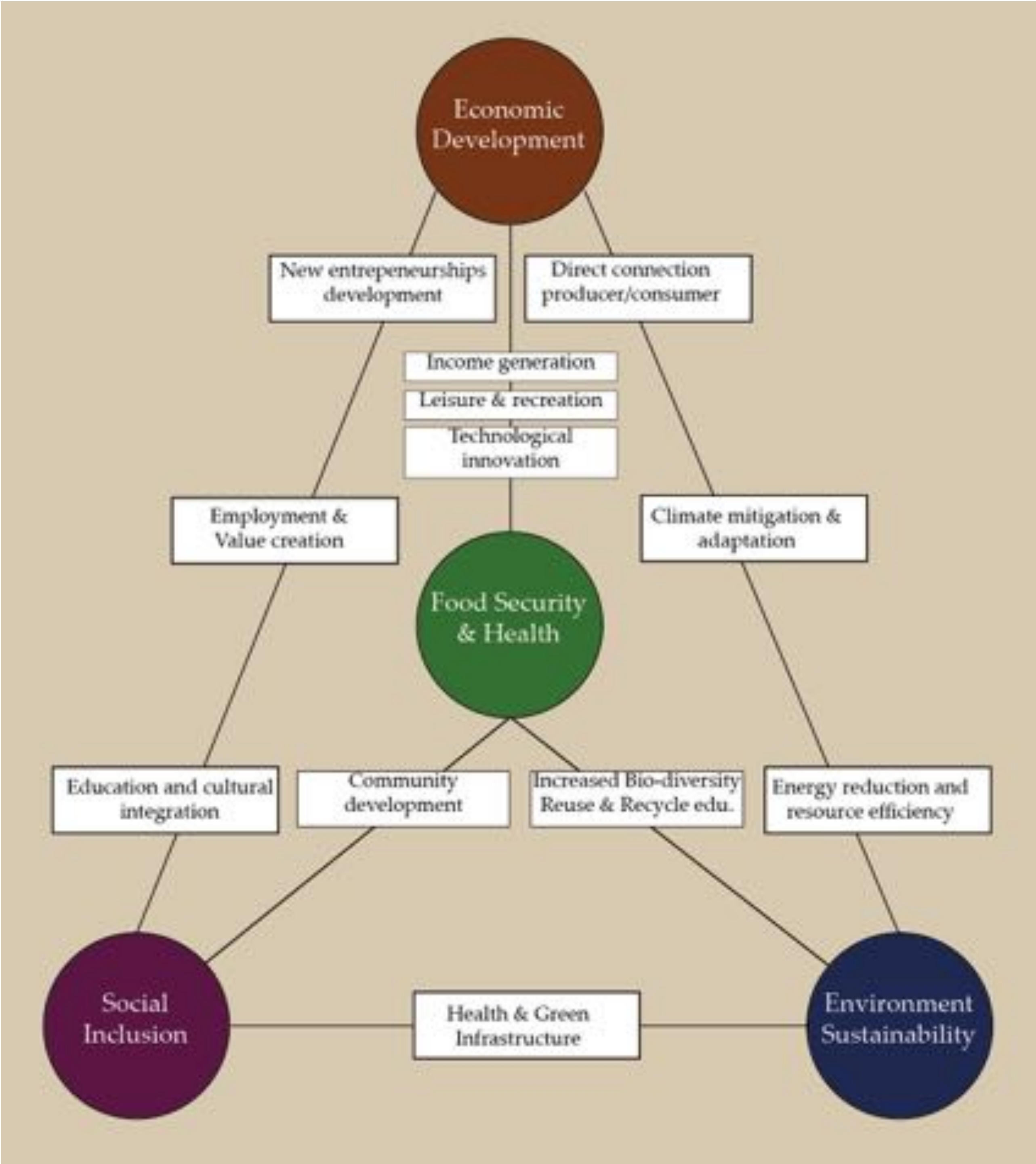
2.1 The four dimensions of Urban Agriculture

The reason of recent success of Urban Agriculture as complementary food production method is not only to be found in its ability to increase global food production, but also in its possibility to improve sustainable agricultural practices in cities, enhancing circular flows in urban areas. All in all, it could be argued that UA offers opportunities for sustainable city development [39]. Thus, UA is to be intended as a multifunctional concept: "[..] i*t refers to food production in and around cities for commercial and non-commercial purposes. It may take place in metropolitan areas, covering urban and peri-urban places, as well as in and around buildings. In addition, UA has a food dimension, as well as non-food dimensions. As such, the concept is clearly different from traditional agriculture in rural areas and industrial food production*" [39].

As reported by the European Parliament Research Service (EPRS) [2], UA involves four different crossing sphere of the urban living:

- food production & citizens' health;
- social development;
- environmental aspects;
- economic development.

Fig. 10 - The interconnections of the Four Dimensions of Urban Agriculture



Source: *Own work based on "Opportunities and Challenges of Urban Agriculture for Sustainable City Development", Erwin van Tujil et al in 'European Spacial Research and Policy'. December 2018*

Food Production & Citizens' health

Core part of UA is related to food production, with the function of implementing Food Security and Food Safety in urban areas. The globalization of food trade, a growing world population, climate change and rapidly changing food systems have an impact on the safety of food: food safety, nutrition and food security are closely linked. "*Unsafe food creates a vicious cycle of disease and malnutrition, particularly affecting infants, young children, elderly and the sick. In addition to contributing to food and nutrition security, a safe food supply also supports national economies, trade and tourism, stimulating sustainable development*" [40]. In developing countries UA is an important part of Food Security strategies, while in developed countries, especially in the US and Western Europe, it is an important tool to implement food safety and fight urban "food deserts"[4].

Social Development

Researches [2,39] have highlighted the potential social impact of urban agriculture, whether for recreation and leisure time, for education or health issues, or for disadvantaged people in the form of specialized-care farming. The introduction of arable areas within the city borders is expected to create new job opportunities that can also educate and employ a portion of the population that is now struggling to work, using UA as community development. This refers particularly to urban gardening as an activity to increase social cohesion between different groups in the society, to provide work and training experience for unemployed workers, and as a tool for crime prevention. Cockrall-King reported some examples in her book 'Food and the city' such as inter-cultural gardens in Berlin, Growing Power Inc. as a training centre for youths [41].Other projects reported in literature [2,24,39,41] stated that UA is used in cities for educational purposes. Through workshops, courses, and tours, urban farmers increase the awareness among citizens about the origin and production of food. Examples include the Manhattan Project in New York described in next Chapter.

Furthermore, the European Parliament Research Service (EPRS) [2] noted how in Europe, UA could be a powerful integration tool for immigrants. In a study published in 2013, Mary P. Corcoran [41] found how migrants gained respect for themselves and others by developing a sense of their own worth through working in the gardens. This was particularly the case for migrant women where the gardens helped restore their socio-economic role, which is central to a person's self-respect.

Environmental aspects

Considering the high environmental impact that RA practices have on ecosystems, UA has been appointed as a possible solution to reduce food production GHGs emissions by reusing and recycling resources such as water and energy already present in cities. A wide range of environmental issues that UA addresses to are included in a 2010 study [43], relating to: waste recycling; air quality; potential impact on the 'urban heat island' (where temperatures in urban areas are higher relative to nearby surrounding areas); carbon sequestration; wastewater filtration; and impact on biodiversity.

Another important aspect of the environmental benefits that UA brings is greening the city, creating green areas within the built urban landscape while closing loops between industrial/ residential buildings with the food production sites. An example can be found in Rotterdam where the so-called 'heat-roundabout' project links industrial firms in the port with large scale agricultural production in the greenhouses of the Westland area [2].

[4] Low-income neighborhoods that are devoid of grocery stores or markets. In those areas people have little or no access to healthy and fresh food because grocery stores have been relocated to suburbs, following more affluent customers.

Economic development

UA may offer potential for recreational, tourist and marketing purposes. Urban farms are open for the public, and organize tours, and as such, they could be compared to other tourist attractions. As said, for many urban farmers, producing food in not necessary the primary goal. Seen from this perspective, it is important to understand that the commercial success of UA projects depends on many factors, mostly related to the ‘mix of activities’ or ‘mix of products’ balancing between high value crops and other selling products [39].

It is possible, through the analysis of recent literature and historical references, trace four characteristics of economic development connected to projects of Urban Agriculture:

i. during times of crisis urban agriculture has made important contributions to food production.

ii. the peri-urban fringe of cities has been identified as the location of larger agricultural activities, where 'significant scope exists for up-scaled social and public enterprises...'. One local authority example from the UK highlights a market garden strategy aimed at generating 1.200 jobs 'catalyzed through urban agriculture interventions on municipal land [44].

iii. Zeunert [44] argues that evidence from the potential use of several well-known green spaces of various sizes in European cities indicates the potential of such areas to generate 'significant economic returns’, if urban agriculture was executed at 25 % (or a more substantial 50%) of their area.

iv. potential opportunities for the development of small-scale rural entrepreneurs. A key finding [45], based on an analysis of more than 100 case studies of urban agriculture enterprises in Europe over a period of three years, was how they are the 'hidden champions' of an urban green development strategy [46]. The common business strategies in urban agriculture include (a) cost reduction, (b) differentiation, (c) diversification, (d) shared economy, (e) experimental and (f) experience.

2.2 Challenges of Urban Agriculture

UA projects could be a way of implementing urban sustainable development, nonetheless, they face a number of challenges and limitations which represent an obstacle to their realization and the success of UA is far from granted. As noted in some researches [2,39,41], UA is not as new as it might appear. While gardening allotments were already a reality during the first industrial revolution used as a food security strategy during industrial times in order to feed the low-class industrial and mining workers, indoor farming with artificial lightening was developed by the General Electrics in the United Stated at the end of the 70s, and failed due to a real market demand.

UA is hindered by a variety of economic, spatial, functional, organizational, and institutional challenges [39]. The major challenges in UA are determining how to monitor, control, and reduce risks in the physical, economic and social environment; and understanding how UA can be a sustainable component of the global urban food systems [39]. Opponents of UA see in the high level of nutrients inputs for livestock and crops, cause for higher pollution concentrations in the long period and health related risks. Moreover, when talking about intensive farming, harvesting in cities might have to add to the already high cost of labor and machineries, the high cost of land and real estate in cities. This may cause a rise in prices of urban-produced food that cannot compete with the equivalent agricultural products. Thus, UA requires large investments to cover high operational costs, including the costs of the infrastructure, energy, and management. This makes it very hard for beginner urban farmers and small entrepreneurs to take initiative or generate enough profits to keep the farm going.

Fig. 11: Opportunities and risks of Urban Agriculture in opposition to Rural Agriculture

Opportunities for urban areas (in opposition to RA)	Risks for urban areas
Physical Environment	
• Less need for packaging, storage, and transportation • Proximity to services, including waste treatment facilities • Waste recycling and re-use possibilities	• Increased competition for land, water, energy, and labor • Reduced environmental capacity for pollution absorption • High levels of air pollutants in cities and microbial contamination of soil and water
Economic Environment	
• Potential Agricultural jobs with low barriers to entry • Non-market access to food	• Limited Production Quantity • Varied seasonal Production Quality
Social Environment	
• Availability of fresh fruits and vegetables • Community Bonding • Access to green spaces • Emergency food supplies • Soil treatment • Environmental stewardship	• Environmental and health risks from inappropriate overuse of pesticides and fossil-fuel based fertilizers

Source: *Game I., Primus R., 'Urban Agriculture' in GSDR 2015 Brief, 2015 based on Hendrickson M. K., & Porth M. (2012). Urban Agriculture —Best Practices and Possibilities. University Of Missouri Division of Applied Social Sciences. Retrieved from*

3. Conclusions: the role of architects and planners in developing UA design strategies

The first chapter of this research wanted to explore the reasons why, in recent years, Urban Agriculture raised that much interest from researchers, city authorities and entrepreneurs. Objective of this analysis was to give a general overview of what are the main areas of interest of UA and which are the limitations to its development in cities.

Out of this analysis, three main globally shared UA goals can be identified both in developing and developed countries, even though the way these goals will be reached is very different:

- Achieve food security
- Shorten the food chain & Reduce the food mile
- Raise awareness & Enhance circularity in urban areas

Achieve food security

Both population growth and the recent economical crisis have caused an increasing of hunger in developing countries and the number of people depending from food aids in developed countries (75% more between 2009-2012) [47]. As previously reported, the current agro-system should increase its productivity of about an average 70% worldwide and 100% in developing countries to feed world's future population. Nowadays, UA contribution to the whole food production system is extremely limited, coming very close to 0% (0,002%) [48].

Under this circumstances, objective of researchers as well as planners, entrepreneurs and environmentalists is to increase the volume of food produced in cities to alleviate the environmental pressure of the agricultural system and feed a greater number of a new hungry population. "*As long as we only trust in large-scale, efficient yet unsustainable productive agriculture, the major food issues will not be solved in the long term. It is necessary to develop city regional food systems in which a large number of beautiful productive spaces are designed that are capable of growing food for the majority of the population*" [39].

Shorten the food chain and reduce the food mile

In a report over the food chain crisis, the FAO [49] warned that globalized trade means not only that food travels further and faster, but so do food-borne pathogens. A corollary to this comment is that the global food chain is also a cause for food diseases, potentially dangerous to humans, due to the poor conditions of how food is stored and transported from the places of production to the ones of consumption.

The food supply chain connects three main sectors: agriculture, food-processing industry and the distribution sector. With the displacement of agricultural lands, and the globalization of the whole food chain, cities rely now on a multitude of food production systems, importing most of their food from other countries and often other continents. "Food mile" is a unit used to measure the distance that a food product travels from where it is produced to where it is sold or consumed: "*I came up with the term 'food miles' to try to help consumers engage with an important aspect of the struggle over the future of food – where their food come from, and how*" said professor Tim Lang who invented the term in the early 90s. Food miles are calculated based on the distance traveled by each food ingredient and the associated amount of carbon dioxide that is released due to the transport means used. "*In terms of resilience, this creates a vulnerability to crisis in the contemporary city: through the utilization of the very global system of trade that it created, the city has become more and more dependent on these trade networks for its metabolism*" [26].

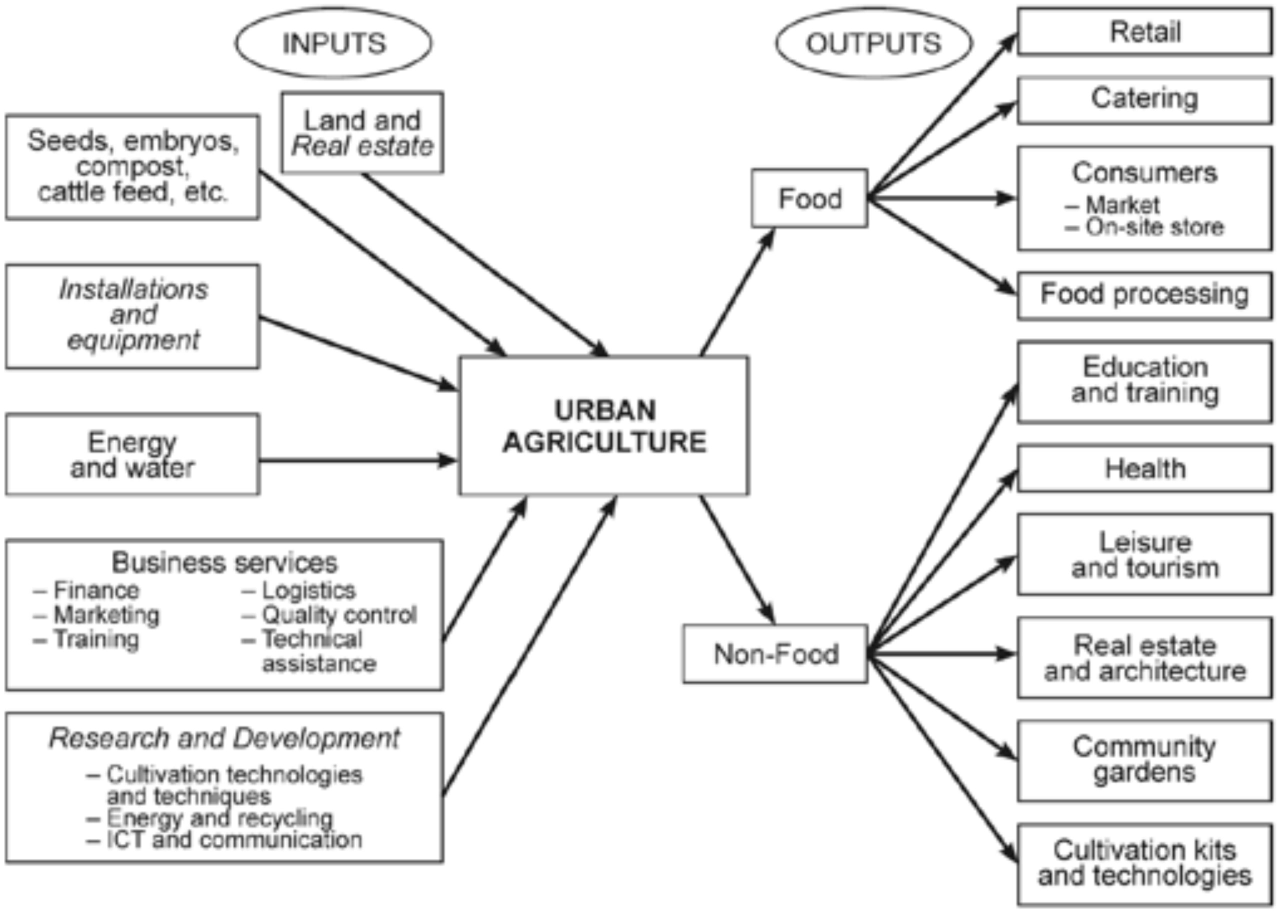
UA projects aim to generate production in proximity to the final users/customers, eliminating the need for long-distance, refrigerated food transportation while reducing food-related diseases [50]. When sustainable growing systems are used, UA projects may allow to dramatically reduce both fossil fuel needs and the associated carbon emissions and air pollution [51].

Raising awareness and Enhance circularity in urban areas

Producing food in urban contexts and making the process directly accessible to the consumers represents a great opportunity for training and raising awareness on environmental sustainability issues as well as the general widespread of knowledge and wellbeing. It is important to believe that a possible way to change our future's course is to reach people, meaning that the implementation of healthy food production and education is essential. Raising awareness in cities on how food is produced, and educate citizens to conscious diets and food behavior is essential to make changes in the current agro-system. In this sense, architecture and urban planning are important tools to show that a different way of producing and consuming food is possible at an urban level, integrating UA projects with complementary educational, leisure and commercial functions.

Cities have resources like water, land, energy and nutrients that are essential for food production, and that often go to waste causing, in many cases, dangerous runoffs for the environment. UA can be a powerful tool to close loops in cities, taking advantage of the already existent resources to produce food.

Fig. 12 - Urban Agriculture in the value chain: Inputs and Outputs of Urban Agriculture



Source: *"Opportunities and Challenges of Urban Agriculture for Sustainable City Development", Erwin van Tujil et al in 'European Spacial Research and Policy'. December 2018*

In conclusions, it is important to understand that UA is not just a food-related practice, but it could enhance cities' sustainable development in the social, economical and environmental spheres of urban living both in developed and developing countries. Under these circumstances, it should not appear odd that architects and planners are now very invested in proposing projects that involve food production in their design. As R. Roggema [48] noted in his book 'Sustainable Urban Agriculture and Food planning', during the past years UA projects were often looked in sectorial ways, often lacking an integrating approach: recently, more projects and researches [52] pushed towards the integration of design aspects (scales, design principles, concepts and strategies, potentials, existing spatial structures and patterns) with environmental parameters (urban metabolism, flows of water, nutrients and energy), economic (business models), social (inclusion, cohesion) and agricultural (productivity) factors. The design and identification of urban spaces destined to UA, as well as a holistic approach to the matter, are fundamental to meet the local food demand implementing the use of resources such as soil, water and energy for food production.

Therefore, it makes sense to invest in UA to counter the most urgent challenges in the city (e.g. fighting hunger, upgrading old industries, or social integration) [39]. Of course, UA is one of the many approaches planners and municipalities can take to implement cities' sustainable development, and not a 'panacea for urban ills' [53]. It is then important that, from a policy point of view, municipalities would integrate UA projects within wider planning and sustainable strategies, being aware of their real potential while taking into consideration the risks and the limitations that might come with them.

However, for UA to address these opportunities, there is a need to have two elements (i) knowledge, and (ii) institutional structures, e.g. policies, laws and incentives [43]. Thus, it is clear that the application and purposes of UA projects is different in developed from developing economies; for the former the primary purpose may be social/recreational or economic, whether for the latter the main purpose is to increase food production to alleviate hunger and increase food security. Furthermore, city planning and legal jurisdictions are very different between countries, as well as climatic characteristics and dietary habits. For all these reasons UA projects must be site-specific, and planning strategies must be tailored for their societal, climatic, economic and political contexts.

For the purpose of this research, we will analyze and propose urban farming design methods in a central-northern European scenario, corresponding to the climatic area CfB: Temperate with no dry season and warm summer (Kottek et al., 2006) [54].

The research aims to fill the gaps in modern knowledge of Technological Urban Agriculture through an extensive analysis of the literature and of the state of art. It has been observed that often, architectonic practice, lacks in precise guidelines on how to proceed when facing urban projects involving agriculture. In this sense, the objective is to define a methodological approach for the design of high-performance off-soil greenhouse systems, such as hydroponic, aeroponic and aquaponic integrated in and on buildings, exploiting the synergies between the built environment and agricultural energy and nutrient flows. New circular strategies are, in fact, more and more used in the planning process to improve urban sustainability and livability. The integration of food production systems within buildings and districts can be a powerful tool to boost the recirculation of resources in urban areas. Hence, this research wants to suggest a possible approach to the matter providing a methodology and necessary knowledge to architect and planners for the integration of food production in buildings that may implement the collection and reutilization of precious resources like water and nutrients.

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Chapter 2: Urban Farming. Practices & Technologies

Framing the field of applications of Urban Agriculture

Preface

With the majority of the world's population already living in cities and the urbanization trends confirming the increasing curve over the next 30 years, cities are at the core of the climate change fight. The need to make cities more sustainable was discussed at the Paris Agreement in 2015 where parties recognized them as important stakeholders, capable of mobilizing strong and ambitious climate actions [1]. The important role of cities in achieving sustainable development is also reflected in the SDGs, in particular in SDG 11 *Make cities inclusive, safe, resilient and sustainable*, where most targets are directly linked to greenhouse gas (GHG) emission reductions, focusing on the implementation of sustainable transportation systems, green buildings and the reduction of the environmental impact of cities [2]. The urge for new planning policies to make cities more sustainable is justified by the recent reports of the Intergovernmental Panel for Climate Change (IPCC), which have estimated that urban areas account for 67-76 percent of global energy use and 71-76 percent of global energy-related carbon dioxide (CO2) emissions [3]. Furthermore, a 2017 report from UNFCCC [4], reported that 20% of the worldwide anthropogenic GHG emissions come from urban infrastructure such as buildings and transportation (of which buildings and construction account for about 70% and transportation for about 30%). In this scenario, the rapid expansion of the urban population equals mass expansions of urban infrastructure. In developing countries the growth rate will be exponential, while in cities in the Americas, Europe, and Oceania, which are not experiencing the same rapid rates of urbanization, it will be fundamental to reduce infrastructure gaps, replacing old aged infrastructure. A 2016 report by McKinsey Global Institute showed that historical underinvestment and the public spending cuts adopted to face the 2008 financial crisis resulted in an infrastructure shortfall of 350 billion dollars per year, most of which concentrated in industrialized European and American countries [5]. Additional investments are then required to meet SDGs goals, and directing infrastructure investment towards low-emission options offers significant mitigation potential and should be ensured [4].

Furthermore, in addition to climate change and urbanization trends, our current industrialized food system will also have to face the important challenge of how to satisfy the rising demand for food, while its productive land is constantly decreasing. The environmental impacts of modern industrialized agriculture are proven to be unsustainable, nonetheless, the need of satisfying a rising food demand could result in making the same mistake of keep relying on intensive food production, implementing the use of chemicals and GMOs to further increase yields of agricultural products [6]. Moreover, food crops are not only competing for land but also water, nutrients, and other resources. In this context, horizontal and vertical surfaces in the city, such as rooftops, facades, squares, and interior spaces, can host a large-scale urban food production, taking off pressure from agricultural land [7]. Cities have resources like land, labor, energy, water, and a ready-made market for food production [8], therefore, it makes sense to produce in urban areas where citizens are not only the final users but also the producers.

The need for new urban green infrastructures, as well as new sustainable solutions for food productions, brought part of the international scientific community to believe that Urban Agriculture may be one of the solutions to climate change adaptation, playing a crucial role in making cities healthier and greener [7]. In this sense, UA should not be considered just as a food-related practice, but instead, as a tool for planners and practitioners to boost cities sustainable development [9]. New urban planning strategies should then be carried on with our food needs in mind. Moreover, reducing CO2 emissions, and implementing new green infrastructure call for a new innovative form of architecture and urban design. Nowadays, it is possible to integrate food production within and on buildings, recycling and reusing resources passing through them while shortening the food chain. New technologies, allowing plants to grow on media instead of soil, permit to harvest of crops in high densely built-up areas where the availability of space often limits the size of the production unit [10]. In this context, architects should consider new off-soil production systems as new construction technologies, understand UA applications, and implement green architecture projects with the integration of the proper food systems.

1 Fields of application of Urban Agriculture: Urban farming, practices and methods

Urban Agriculture can be defined as the activity of planting food and breeding animals within and around cities. In the past 20 years the evolution of urban agriculture resulted in different definitions and conceptual developments. The United Nations Development Program (UNPD) adopted as definition the one of Smit et al. (1996) [11]. It defines urban agriculture as an industry that produces, processes, and markets food, largely in response to the daily demand of consumers within a town, city, or metropolis, on land and water dispersed throughout urban and peri-urban areas. Mougeot (2000) [12] submitted a revised definition, where urban agriculture is defined as an industry located within (intraurban) or on the fringe (periurban) of a town, city or metropolis, which grows or raises, processes, and distributes a diversity of food and non-food products, (re-)using largely human and material resources, products, and services found in and around that urban area. Nonetheless, the board applications of UA on different scales and with different focus make it harder to adopt a commonly agreed definition [13]. For this reason, it is important to understand UA aims, location and cultural/climatic context before approaching new UA activities.

In this regard, this research intends to exclusively focus on the integration of food crops within the built environment, exploring the role of architects, engineers and planners in proposing and designing UA projects, excluding animal husbandry and livestocks. The activity of growing plants within and around city borders goes by the name of Urban Farming (UF), and was defined by Orsini et al. (2013) as those applications of UA that may include the production of all fruit and vegetable food crops (including roots, tubers, tree nuts, aromatic plants, and mushrooms) or medicinal and ornamental species, preferring to grow short cycle and highly perishable crops within urban areas, while peri-urban areas are mostly dedicated to medium or long cycle crops and orchards [14]. From now on, the acronym UF and UA will be used as synonym and referred to the above written quotation.

1.1 Broad application of Urban and Peri Urban Farming

The variety of UF forms can be classified in various ways, depending on its actors, purpose, land use, scale, location, property, technology, and production system [15]. The concept refers to the production of food crops within cities and around them. It includes commercial and non-commercial activities and covers food processing as well as other activities in the food value chain [16]. That makes UA a multi-dimensional concept [16] that can deeply vary from project to project. An analysis made by Tujil et al. [13] identified several applications of UA projects, and categorized them into nine macro typologies depending on the location, the dimension, and the strategic focus (Fig. 1):

1_ Community Garden
Community gardens are sections of land collectively gardened for the specific purpose of growing fruits, vegetables, and/or herbs for self-consumption [17]. This typology covers various types of gardens, including demonstration gardens, horticultural therapy gardens, job-training gardens, neighborhood gardens, inter-cultural, etc [13]. Community gardens aim to improve locals

wellbeing, urban health, social inclusion, and promote active citizen participation [17].

2_ Institutional Garden
Institutional gardens have a similar concept and purpose to community gardens, with the only difference that food production practices are managed by institutes like schools, hospitals, prisons, and other organizations [13].

3_ Guerrilla gardening
The concept of guerrilla gardening can be explained as an informal movement with the purpose to regenerate forgotten spaces and bring communities together [18]. The activity of guerrilla gardening can then be either legal or illegal, with actors sometimes restricting access to colonized land. In this case, it can also assume the name of â€˜illegal gardening [13].

4_ Urban Farm
Not to be confused with the broader concept of Urban Farming, urban farms are full-fledged farms within the city borders where professional farmers grow commercial food using advanced farming methods and technologies [13].

5_ Vertical Farming
Vertical farming is a concept that earned great success over the past decade, as it allows to intensively grow food on multiple levels inside buildings. Indoor production is permitted by the use of off-soil technologies such as hydroponic, aeroponic, and aquaponic systems. In the book The Vertical Farms: Feeding the world in the 21st century, the author saw in the implementation of the vertical farm inside the cityscape a potential solution for two problems: (i) production of food crops to feed a growing urban population, and (ii) freeing up farmland and allowing it to return to its ecological setting [19].

6_ Plant Factories with artificial lighting (PFAL)
PFAL is a specific typology of indoor production, which exclusively uses LED lights to enhance plants photosynthesis processes. PFALs are closed systems where the use of resources is maximized. To enhance productivity there are no interactions with the external environment, and the inner climatic conditions are adapted to plants' needs. PFALs are then not influenced by exterior climate.

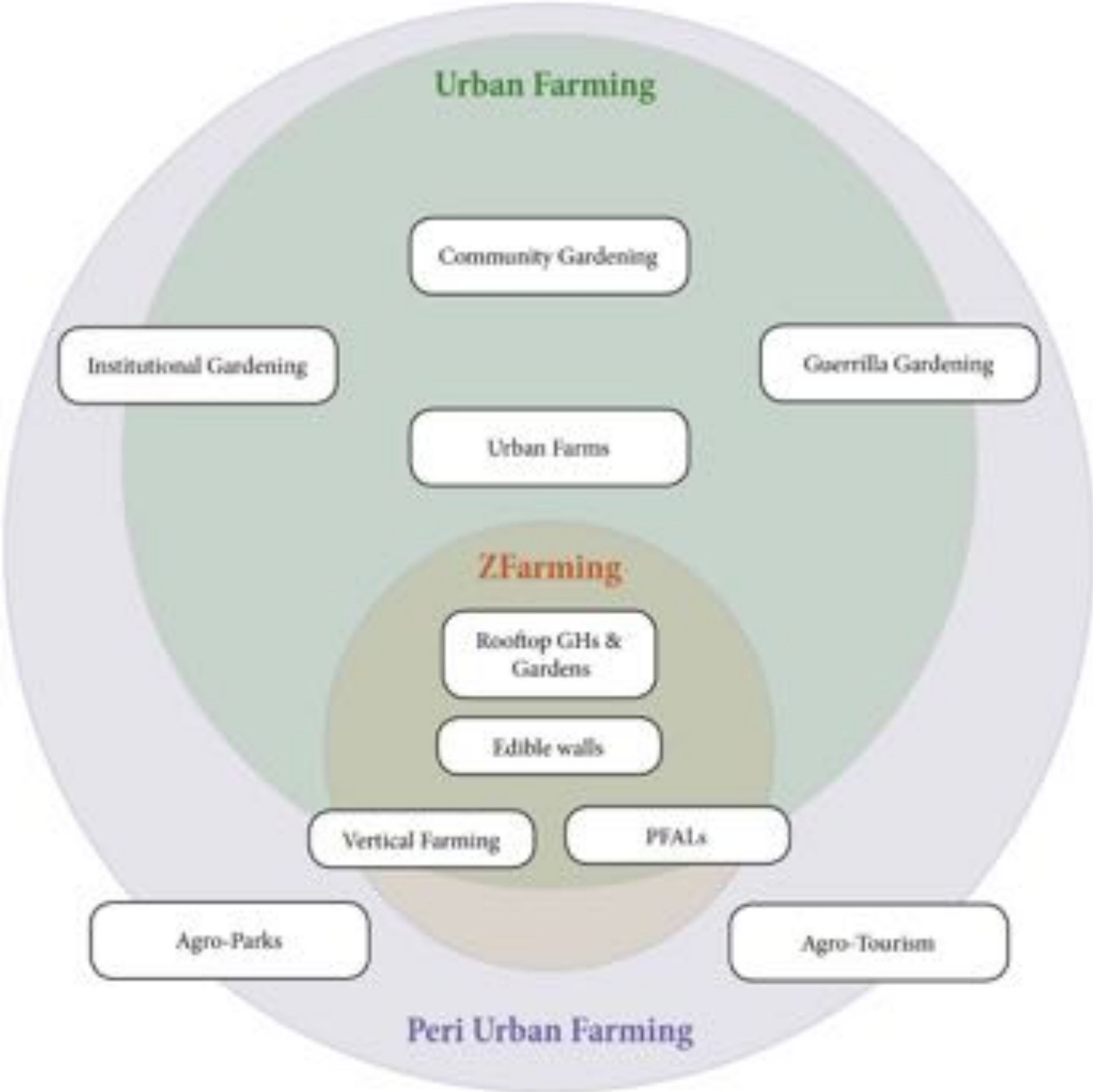
7_ Zero-Acreage Farming (ZFarming)
The term Zero-acreage farming (ZFarming) is used to describe all types of UA characterized by the non-use of land or open space [13]. Such production types might include the installation of rooftop gardens, rooftop greenhouses, edible green walls as well as further innovative forms such as indoor farms or vertical greenhouses [7]. Therefore, ZFarming includes all possible types of urban farming in and on buildings that do not need soil or land to grow.

8_ Agropark
An agropark is a spatial cluster of agro-functions and related economic activities. It brings together natural resources-based production and processing along with industrial principles [20]. Agroparks are intended as production places where food production and commercialization of agro-products are connected, creating a meeting place where actors from academia, entrepreneurs, and industry come together to generate innovative ideas [20].

9_ Agro-tourism
Agro-tourism is the activity of farming recreational parks to produce food and offer services and facilities for tourists. Combining food production with leisure activities is a way for Agroparks to promote integrated urban and rural development in a manner that can counteract some of the

negative impacts of urbanization [21]. Agroparks are usually located in peri-urban areas, as they need huge operating spaces to work effectively [13].

Fig. 1: Broad applications of UF and PUF



Source: *Own work based on the classification made by Speech et al. (2014) [7].*

Not every type of UA fits in a single category [13], and overlaps between the types exist and are easily found in UA projects. Often, different categories can complement each other, for instance, rooftop gardens can be community gardens and also fall into the category of ZFarming [13]. In the same way, Agroparks can be a type of urban farms that sell food products in the same place where they are produced. Nonetheless, a great difference between those categories can be identified linked to two macro-dimensions of food production: use of land and food technologies. Whereas the common purpose is to shift towards sustainable intensification of urban crop production [14], in highly constructed urban areas land availability is a great limit for production.

Therefore, in densely built-up areas, where the availability of space often limits the size of the production unit, the use of soil-less technologies represents new opportunities to increase urban crop yields [7]. In this regard, ZFarming (including Vertical Farming ad PFAL concepts) is the best solution to achieve high yields in very limited urban spaces [7].

Fig. 2: Different Urban Farming projects

1: Allotment gardens in Bologna

2: ZFarming: A rooftop greenhouse in New York

3: Vertical Farming: Ocado Plant Factory in UK

Credits: 1 - Michele Mellara; 2: Ari Burling from https://www.urbangardensweb.com/; 3: Jones Food company

1.2 Farming in and on buildings: potential impacts of ZFarming

To integrate agricultural activities within buildings in a highly dense urban environment, ZFarming offers the best solution to achieve intense production while minimizing the use of land. The term was introduced to describe all types of urban agriculture characterized by the non-use of farmland or open space, thereby differentiating building-related forms of urban agriculture from those in parks, gardens, and urban wastelands [7]. Hence, ZFarming differs from ground-based UF, of which it can be considered as a subtype. It can be considered as a complementary practice of ground-based UF, that offers opportunities for resource-efficiency synergies between buildings and farming [22]. Implementing ZFarming models within cities requires new regulation frameworks and advanced technical knowledge of ZFarmers, which have limited today the expansion of these types of UF in respect to ground-based practices. In research conducted by Thomaier et al. (2014) [22], they studied 73 different ZFarming projects, and even though each farm had its specific goals, three main common strategic orientations were found:

1. *Sustainable food production* which was considered to have high transformative potential: ZFarming offers new possibilities to implement sustainable models of food production. The integration between buildings and the agricultural systems is an opportunity to redirect urban resources like energy and water from one entity to the other. Research for new technical solutions is then fundamental to achieve new forms of synergies between buildings and farming. In this regard, further, development is needed to make ZFarming more accessible. As of today, most of these experiences are located in high-income neighborhoods [22] failing to feed the low-income population and focusing more on the qualitative improvement of the food system. In developed countries, where more and more people are becoming aware of the benefits connected to a correct alimentation [8], food systems are increasingly called upon to address issues such as transparency, health, sustainability, resilience, fairness, diversity, and equality [22]. In this context, integrating food production within urban communities can create an alternative sustainable supply chain, where the food-mile is reduced to zero and consumers have are directly connected to the places of production [23].

2. *Education and social commitment* (medium transformative potential): As described in the first chapter, one of the shared goals of UA projects is to promote conscious consumption behaviors and raise awareness in consumers regarding food and health. The possibility of integrating ZFarming activities right where people live may enhance citizens' participation in educating programs, teaching new ways of sustainable food production, promoting healthy lifestyles. In this regard, openness and inclusivity are some of the precepts of UF projects, fostering social inclusion in contemporary dense urban areas where people with different social and economical backgrounds live.

3. *Urban qualities* (low transformative potential): ZFarming as a subtype of UF is not just a food-related practice, offering non-food and non-market activities that can implement urban life quality on a local scale. Recreational spaces can be found in ZFarming projects contributing to strengthening people's sense of community. The idea is to give citizens a new green oasis where they can participate in local food production accompanied by leisure and educational activities.

The strategic objectives of ZFarming projects, as well as its peculiar characteristics of producing food without using land space, make this special subtype of UF particularly interesting for professionals involved in sustainable urban construction and planning. Architects, planners, and engineers recently developed an increasing interest in ZFarming methods to implement green buildings design, trying to connect aesthetic, functional, and ecological principles [24]. The need to reduce cities' resource consumption, create sustainable infrastructure and plan more inclusive cities while reducing the food chain make ZFarming a powerful tool to implement new green urban designs [25]. This might be particularly true for Building-Integrated Agriculture (BIA), a specific subtype of ZFarming which is defined as the practice of locating high-performance off-soil greenhouse systems, such as hydroponic, aeroponic, and aquaponic, on and in mixed-use buildings to exploit the synergies between the building environment and agriculture-like energy and nutrient flows [7]. BIA is considered to be highly compatible with sustainable bioclimatic design principles [26]. Nonetheless, as noted by Thomaier et al. (2014) [22], in many cases the synergies between buildings and farming are not completely fully exploited. This is probably since most BIA projects are integrated with existing buildings that are not necessarily compatible with the food infrastructure. On the other hand, ZFarming and BIA are powerful tools for the retrofitting of abandoned buildings and old industrial sites. Integrating food production in abandoned sites is an opportunity to bring back to life post-modern ruins, creating new mixed-use buildings that can generate revenues and implement local living quality improving the urban landscape [27].

In conclusion, ZFarming and Building-Integrated Agriculture can be considered as new design tools to foster cities' sustainable development. In this regard, new planning strategies, as well as new legislation and regulations must be adopted to facilitate the retrofitting and the new construction of mixed-use buildings where food production and other living and social activities are interconnected. To properly use these tools, it is important to understand the advantages and limitations that they present based on literature and previous experiences.

1.3 Advantages and limitations of ZFarming

As stressed in several types of research [13, 28, 29] UA projects touch the four dimensions of sustainable development: food security & health, social, economic, and environmental. To understand the potential of ZFarming, it is important to assess the advantages and limitations of UA in each of these four dimensions. This first assessment is extrapolated from extensive literature research and will be developed furthermore in the next parts of this chapter after an in-depth analysis of selected case studies of ZFarming and BIA.

Food Security & Health

UA projects are often linked to several health benefits: from enhancing fiscal activities while gardening to improving access to food in urban areas. Nonetheless, ground-based UA can present some hazards if not traded carefully: the proximity of industrial plants, dump sites, and traffic areas may contaminate the plants or the soils; water can be poisoned by heavy metals and contaminations could be fatal to plants and dangerous for humans [30]. Furthermore, in densely populated urban areas, the risk of food-borne diseases throughout the population is high [7]. In the case of soil-based ZFarming, risks of food contamination connected to air pollution are to be taken seriously into consideration. In this regard, rooftop greenhouses and indoor farming may dramatically reduce the risks of pollution and food pathogens, being the production carried on in a controlled environment. Indoor production is said to reduce the use of pesticides and herbicides [31] improving food quality and people's health. The use of off-soil technologies such as hydroponic or aquaponic systems can also guarantee higher yields than conventional soil-based agriculture being 5 to 7 times more productive [32]. Whilst this may be an advantage, limitations concerning indoor production are related to the use of these advanced technologies, which may require technical backgrounds, limiting the access to the production of a great part of the local community. On the other hand, a controlled environment can be very fragile, and risks of plant diseases due to human cross-contamination can increase with multiple people working or visiting the production spaces [7].

In conclusion, ZFarming practices might guarantee safer food, being distant from the main roads and detached from the ground. Moreover, advanced production can guarantee higher yields and reduce the risks of food-borne diseases. Nonetheless, the application of advanced technologies and the relatively small productive spaces represent a limitation in the involvement of a huge part of the local community, as well as a limitation for several crops (like cereals, root vegetables, and fruit trees [7]) to be produced. Hence, UA and ZFarming initiatives cannot supply citizens with all the food they need [7], nonetheless, they can provide access to healthy fresh food in food desert areas, where the lack of food markets and retails is relevant, both in the northern and the southern hemisphere.

Dimension	Advantages	Limitations
Food Security & Health	Lesser risks of food-borne disease and soil contamination [22] [7].	In soil-based rooftop farming, air pollution might endanger the crops and people's health [7] [22].
	May reduce food desert areas in developed countries, while providing more accessible food in developing regions of the world	Food-borne diseases might affect plants due to the cross contamination with multiple actors involved in the production [7].
	Increased yields and greater access to fresh food within the larger community [30] [22].	Advanced technologies limit the access to food production to parts of the local community [22].
	Address the issues of transparency, fairness and equality in food production, bringing closer consumers and producers [22].	
	May improve fruits and vegetables, consumption, or willingness to try fruits and vegetables, raising awareness on healthy diets [33].	
	Controlled production environments with improved air filtration and steady humidity and temperature have downstream health benefits on other building's residents [30].	

Social Dimension

Most of the advantages connected to the social dimension of urban food production are connected to the possibility of educating people on healthier diets and sustainable food production while giving them new job opportunities and meeting places. Education is a powerful tool to boost social inclusion, especially in mixed-income and multicultural western cities. In this context, ZFarming has a huge potential in providing learning and educational facilities inside urban areas [7], connecting production sites with multifunctional buildings. For instance, placing rooftop greenhouses on top of schools represents a powerful hands-on learning tool to teach children the pillars of sustainable food production. The synergy between schools and rooftop greenhouses, used as an extension of the teaching spaces, provides new opportunities for practical learning [34].

ZFarming initiatives can also implement forms of self-made agriculture for personal use, contributing to reduce food-desert areas [30]. Nonetheless, BIA practices using off-soil techniques require high-budget investments that may produce high-value crops that are not affordable to the low-income population [35]. Moreover, the high investments required and the consequent high value of the crops may push investors to implement BIA projects in those areas of the city where wealth is more concentrated, increasing the gap between wealthy areas and low-income neighborhoods in the same city [36]. Hence, whilst the soil-less production represents an objective advantage to implement diffuse systems of urban food production throughout the city, its costs may result in exclusive initiatives rather than inclusive ones. On top of that, it is easy to encounter a form of skepticism towards new advanced, off-soil production methods [7]. Interviewed consumers tend to prefer organic agriculture and soil-based UA rather than off-soil-grown food [36].

Dimension	Advantages	Limitations
Social	Foster opportunities for social inclusion, bringing people together and creating spaces to meet [30][22][7].	High initial costs may limit investments in low-income neighborhood, increasing the gap between wealthy and poor areas of the city [7] [30].
	Raise awareness on health-related topics such as sustainable food production and healthy diets [7][30]	High-value crops may not be accessible for low income population, failing to achieve food security in food desert areas [7][35]
	Promote education for young people and low-income citizen giving opening to them new job-opportunities in the urban agro-industry [30].	Advanced technology require an existing know-how, limiting job opportunities to non educated people [7][30].
	Foster education for youngster and children, teaching sustainable life-styles and respect for the environment [7][34][30].	Forms of skepticism regarding off-soil production may discourage entrepreneur in investing in off-soil ZFarming [7].

Economic Dimension

Bringing food production within the city boundaries has been considered an important asset to regenerate the distressed area, increase proprieties value and encourage further investments [30]. When talking about ZFarming initiatives, financing plays a key role in transforming projects from ideas into reality. The high cost of buildings' retrofitting, combined with the high costs of technological installations and possible structural consolidation, prevent many operations from being realized [7]. Furthermore, food production might compete with other building's functions: in the case of indoor production, it could be more valuable to regenerate buildings for housing or commercial purposes rather than for food activities. At the same time, rooftops can be used to install solar panel plants, receiving financial aids from local municipalities [30].

In this scenario, young entrepreneurs and small start-ups might be discouraged to carry on ZFarming projects. Nonetheless, UF projects have the potential to attract capital [30], and real estate developers are growing fond of the idea of improving the sustainable design with the integration of food production practices [22], sharing the cost of co-financing with new urban farmers. Transforming abandoned buildings into indoor farming is also catching the attention of developers and municipalities [22]. Renovating the urban heritage and forsaken industrial architecture is, in fact, a successful sustainable planning strategy [38]. Nonetheless, the high costs of some ZFarming projects and the increased value of proprieties and land connected to these investments may cause the displacement of disadvantaged categories in low-income areas, marginalizing them, pushing them out of their “land” [39].

In conclusion, many aspects of the Economic Dimensions are connected to the social aspects of ZFarming projects. Indoor farming and off-soil technologies, which allow high yields and may improve food production overall sustainability, have the potential to create high revenues. To achieve that, new financing sources and adequate planning are required in order not to exclude low-income parts of the population from these initiatives and invest in educational and social spaces to make ZFarming more inclusive.

Dimension	Advantages	Limitations
Economic	Attract investments for the redevelopment of distressed urban areas [7][22][30].	Investments in distressed urban areas might increase land value, marginalizing low-income citizens [30][39]
	Off-soil intensive production can generate high revenues, creating new job opportunities in the field of food production and other related activities [22][30].	High initial costs might be unbearable for small entrepreneurs and start-ups that will be immediately cut out of the market [7].
	Integrating food in buildings may improve sustainable design, attracting investments from real estate developers [7][22].	For commercial oriented ZFarming projects, the high operational costs might be an obstacle to maintain long-term revenues [30][40].
		Financing sources are vital to start ZFarming projects, thus their realization highly depends on external investors [22][7][30].
		Profitability of ZFarming cannot be guaranteed only by food production only [30].

Environmental Dimension

Urban agriculture has been promoted as part of the transition to a more environmentally sustainable food system [30]. Applications of UA are also considered to have a great potential in favoring the transition towards lower-carbon cities, making them more resilient against food shortages in case of future economic or pandemic crisis [41]. Further environmental benefits of UA are addressed to resolve climate change issues, enhancing resource-saving and resource efficiency [7].

In this regard, ZFarming projects are strategic in the development of green buildings, recycling resources, and reducing food transport emissions. Eco-effective architecture design can be influenced by integrated agriculture systems, exploiting the synergies between buildings and food production spaces. For instance, water recycling and grey-water usage in BIA can dramatically reduce water consumption in urban food production [42]. At the same time, energy efficiency can be implemented by integrated food systems, using greenhouses and production spaces as cooling, heating, and energy recycling entities. Rooftop gardens, and especially rooftop greenhouses may work as an additional insulation layer, with the double potential of (i) avoiding heat loss and (ii) cumulating heat that can be exchanged with the building [7]. Integrating gardens and greenhouses on walls and rooftops can also contribute to reducing the urban heat-island effect thanks to plants' transpiration, adding new food and green spaces in highly dense urban areas [30].

Thus, ZFarming projects can be a viable solution to mitigate climate change and help planners and architects in developing more sustainable cities. Nonetheless, combining the application of advanced resource-recycling technologies with food production systems requires high investments and it may be difficult to apply in case of retrofitting projects. The building-integrated energy use and food production issues are the most crucial to be solved In this regard, planners, engineers, architects, agronomists, and all the other disciplines involved in the development of BIA projects must work together to overcome those issues. Implementing resource efficiency is, crucial to enhancing the sustainability of BIA projects. Soil-less agriculture and indoor production are, in-fact, resource-intensive operations that may increase GHG emissions and water usage in urban settlements [43], in particular, vertical farms are highly energy consuming compared to solar-powered greenhouses.

However, if appropriate crops and methods are chosen, ZFarming projects have the potential to dramatically reduce GHG emissions compared to industrial ground-based agriculture [44].

Dimension	Advantages	Limitations
	Shortening the food chain with potential reduction of GHG associated with food transportation [30][7].	Transport foot-print is just a small percentage of current food system footprint. Reducing the food-mile might not result in actual gain in terms of GHG emissions [7][30][46].
	Provision of new design strategies and tool for the development of green buildings, fostering synergies between buildings and food systems [7][22].	Small-scale fragmented ZFarming projects might not be efficient in terms of resource consumption [30].
Environmental	Reduction of the urban-heat island thanks to plants transpiration [30][45].	Intensive indoor farming and soil-less systems require high energy inputs to operate. Appropriate crops and methods must be chosen to avoid an increase in GHG emissions for advanced urban production [30][22][43].

Dimension	Advantages	Limitations
	High potential for water recycling in closed off-soil systems. Possible integration of grey and rain water to reduce to almost zero water inputs for food production [7][30][22][43].	
	Implementation of buildings' energy efficiency in cooling and heating processes, exchanging resources between the production spaces and the building [7][22][43].	

1.4 Conclusions

Cities are focal points of climate change fight and sustainable development of urban areas is a priority in most industrialized countries. In this context, ZFarming can provide planners and architects with new solutions to implement green architecture and green infrastructure. Understanding advantages and limitations of building-integrated agriculture is crucial to develop smart solutions, enhancing the synergies that buildings and food systems can create when juxtaposed.

Food production is the core of ZFarming project, although "there is more to UF than just food production" [22]. Social, educational and economic goals must be taken into consideration when approaching building-integrated agriculture as they might be the key for the success of ZFarming initiatives. Defining the environmental aspects of this projects is crucial for architects and engineers to justify the integration of food production systems within their design. To this regard, ZFarming can be a source of inspiration for the development of green buildings, both in renovation or new construction projects [7]. Nonetheless, the use of advanced indoor and hydroponic technologies must be approached carefully and the cooperation with other practitioners like agronomists and engineers is fundamental to fully integrate the food spaces within the building structure.

In order to better understand how ZFarming concepts can shape the architectural design, the next two parts of this chapter will be dedicated to the analysis of 25 selected state of the art projects. The case studies were chosen based on literature review, conference attendance and personal experience. All the selected projects are located in industrialized area of the world, with the intention of focusing on indoor and hydroponic farming integrated in buildings. The objective is to determine strength and limitations of these projects, primarily assessing their contribution in two of the four Urban Farming dimensions: Food & Health and Environmental.

2. Construction of the state of the art: recollection of advanced UF projects & experiences

Urban Farming can take many forms and has several applications. From an architectural point of view, UF can be used by planners, engineers, architects, and agronomists to shape the cities of the future enhancing circularity, promoting more resilient urban spaces [7]. In this regard, ZFarming concepts allow practitioners in the construction world to take advantage of food production technologies to implement their design, fostering new urban food policies and markets. For a better understanding of what ZFarming practically means, and how it can be adapted to improve architecture quality, we selected, analyzed, and categorized a slot of 21 states of art projects.

The first step of the analysis was to divide the selected projects into four macro-categories representing six different urban scales:

1. **Neighborhood / District**
2. **Urban installation**
3. **Building**

3.1 **Rooftop greenhouse**

3.2 **Facade**

4. **Product design**

The six categories represent the scale of the selected projects. This choice was made to make it easier to compare projects of similar scale and goals.

The second step was to identify four sub-categories, that could define every project. These categories are:

- Main Function (Social, Educational, Food Production, Promotional)
- Type of project (Renovation or New Construction)
- Food technology (High / Low)
- Project Status (Built, About to be built, Project concept)

Based on the division in Macro and micro categories, the analysis sheets were structured following this logical process:

- Introduction on the project
- Details of the selected project
- How the selected projects reach circularity goals
- Food production characteristics and plants integration

The objective was mainly to assess the relationship between food production and the environmental dimension. Special focus was put on understanding how ZFarming projects can implement circular features in buildings and districts, by enhancing resource circulating strategies.

The strict structure of the sheets allowed us to make a comparative analysis of the selected project based on two different focal points:

1. **Circularity: goals and approaches**
2. **Food production: goals and technologies**

As a conclusion of the analysis, we will analyze the juxtaposition of these two focal points, not considering them as separate entities, but as three fundamental parts of ZFarming projects.

LEGEND

MACRO CATEGORIES

Scale

Urban - Neighborood

Urban installation

Building

Rooftop

Facade/Envelope

Interiors/Product design

Micro CATEGORIES

Functions

Research

Commercial

Educational

Promotional

Type of Project

Renovation **R**

New Construction **NC**

Food tech

Technology based **T**

Technology + Gardening **TG**

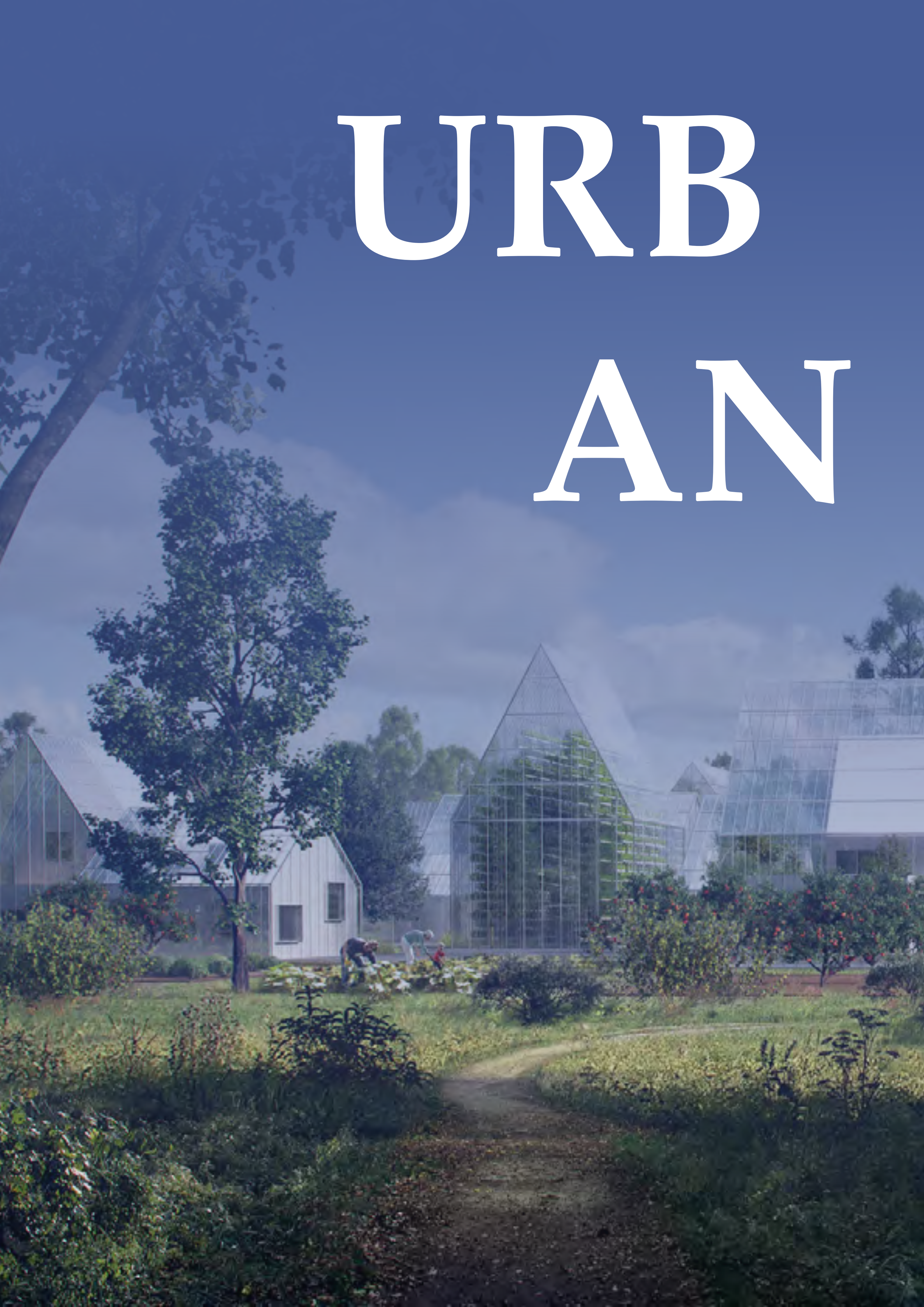
Project status

Built

About to be built

Project idea

URB
AN



SCALE

U01 - Bajes Kwartier, Amsterdam (NL) - OMA

INTRODUCTION

The former Bijlmerbajes in Amsterdam, a prison complex in the South-East of the city built in the 1970s, will be redeveloped by a team lead by real estate developer AM, in which OMA is responsible for the masterplan of the 7.5 ha site, as well as the design of a significant portion of the 135,000 m2 building development.
The towers of the Bijlmerbajes have been a landmark in the periphery of Amsterdam for decades. With the city's urban expansion to the north, south, east and west, the prison complex has gradually become a geographic center of Amsterdam's new urban development, and can develop into a vibrant civic and cultural space.

The original prison masterplan was comprised of six linked towers and an administrative building, with a series of courtyards and separate gardens. In OMA's masterplan, the island character of the prison enclosed by walls is conceptually preserved, yet linked at several positions through new pedestrian and cycle bridges. The Bajes Kwartier is structured as a series of four clusters, each one with a strong character and program mix, to be linked via a central pedestrian + cycle path on the footprint of the former prison distribution spine, the Kalverstraat. One of the existing towers will be transformed into a Green Tower, a vertical public park to showcase Dutch urban farming concepts and a viewing platform for the neighborhood. The Bajes Kwartier will become a largely car-free environment, with gardens and areas for recreation and fitness.

The land and buildings property of the Dutch government's Rijksvastgoedbedrijf will be sold to real estate developer AM. The new development includes around 1,350 new apartments for sale and rent, and a large variety of typologies including 30% of social rental apartments. The sustainability strategy calls for 100% energy neutral buildings and the reuse of 98% of the existing materials. Concrete will be recycled and reused, prefab elements from the existing walls are to be reused as cladding for new residential buildings, prison bars will be used as balustrades, and the cell doors are to become edge panels for the new pedestrian bridges. A system to recycle organic waste into soil and energy will be implemented, and excess heat from a nearby Data Center will be reused for the heating of the apartments.

The project is scheduled to begin in 2019, with an expected completion date in 2023.

DETAILS

Client: AM Real Estate

Year: 2017

Starting construction: 2019

Design: OMA + FabriCATIONS + Lola Landscape

Project area surface: 7.5 ha

Total built area: 135000 m^2

Residential units: 1350

% Social housing: 30%

Extimated populaton: 3000 pp

ENHANCE CIRCULARITY

The aim is to minimize the impact of construction on the climate. In the redevelopment, three levels of circularity are applied where the CO^2 footprint is minimized, natural and healthy materials prioritized and historical identity strengthened. The new buildings in Bajes Kwartier are the first buildings of the Netherlands to participate by take 'BAMB' the material banks of the future to become.

1. Transformation

Transformation is about physically preserving buildings or building components and functionally repurpose them. Because of this, there is less need of new building materials. In the Bajes Kwartier also the underground pipe line is completely reused, just like parts of the prison wall.

2. Reuse & Recycling

In addition to transformation, building components of the former Bijlmerbajes will be reused and visible in the new buildings: this is how the façade of the former Kalverstraat is incorporated in the plinth of the residential buildings and become parts of the facades in the student housing. The bars will also come back as balcony shielding for homes. The demolition of parts of the complex will become the materials for pavements and for the granulate applications in the concrete for facades. The aim is to reuse 98% of the materials of the former towers.

3. Circular new construction

Proposed materials consist of a mix of renewable and old reused materials: those choices result in an average score the module MAT1 of BREEAM of 7 (= 6 + 1) points.
This improves performances of the construction and allowed to patent the construction of every building.

The passports of Bajes Kwartier are included in the 'Buildings as Material Banks' platform (BAMB) where BAM participates.
Bajes Kwartier Amsterdam will be the first project conform to this standard. In other words: Bajes Quarter will be the building material bank of the future.

FOOD PRODUCTION - The Groene Toren

De "Groene Toren" (literally "the green tower") is the core of the whole neighborhood. Most of the food production will be host here and it is expected to satisfy the demand of the 3 thousands inhabitants of the new Bajes Kwartier. Rainwater is harvested and collected in the building basement, to be reused for food production and other processes around the building. Food is produced on the fourth floor and consumed in the café on the top floor and in the restaurant on the ground floor. Organic Waste is collected from the tower and the surrounding buildings to be transformed in compost, which is used for the vegetation around the building. As a result of this process, Energy is generated in the waste transformer to be used in the building.
Additionally, a Power Nest generates electricity from wind and solar power, to guarantee regular provision of sustainable energy.

The design of the new Green Tower builds upon the original organizational principle of the tower: three blocks separated by two supporting levels. Each block has its own set of architectural interventions. The architectural interventions mostly consider the implementation of natural green (i.e. gardens, green facades) and technical green (i.e. sustainability-oriented technology and infrastructure). As a result of the organizational principle, each block has its own climate, biotope and technical function.

A striking yellow staircase connects the blocks and acts as a continuous spatial sequence to guide visitors through the building. The yellow stairs start with a ramp which brings the visitors from the public square outside to the entrance level of the Green Tower, and leads the visitors all the way up to the panoramic cafe on the top floor, where food produced in the Green Tower can be consumed. Along the yellow path, visitors can experience public program and resting areas, in direct visual relation with the technical equipment that supports the sustainability processes of the building.

FOOD/PLANTS INTEGRATION[3]

A lot of differen food and non-food plants will be produced in the experimental garden located in the the east part of the tower, including:

Consumable flowers
Curcubita
Solanum Melongena
Cynara Scolymus
Viola Tricolor
Chrysanthenum
Brassica Oleracea

Fragrant plants
Lavander
Coriander
Peterseil
Hyssopus
Salvia
Laminacae
Illicium Averum
Wisteria sinensis

Vertical plants
Rosa
Hedera
Fargesa Murielae
Wisteria Sinensin
Illicium Averum

Berry shrubs
Ilex x Miservae
Mahonia Aquifolium
Coruns alba sibirica
Berberis thunbergii
Callicapa dichotoma
Ilex Verticillata

Ornamental grass
Achillea Filipendulina
Pennisedum Alopecuroides
Calamagrotis Acutiflora
Stipa Tenuissima
Stipa Aruncidanea
Carex Testacea
Calamagrotis

U02 - ReGen Villages, Almere (NL) - EFFEKT

INTRODUCTION

The ReGen Villages project was first introduced to the United Nations community in the form of a Global Sustainability Development Report authored in 2015. Titled "*RegenVillages – Integrated village designs for thriving regenerative communities*", this document outlines plans for developing symbiotic resource systems at neighborhood scales and with closed loops. The specific concept outlined in this report was aspirational and has since proven to be highly desirable by the general public through its global mass media exposure at the 2016 Venice Biennale for Architecture.
Today, **the operational goal of ReGen Villages is focused on establishing a perpetual state of regenerative resource units for community consumption, that under ideal conditions, require no external inputs for water or electricity**. In this respect, system capacities would support approximately 150+ residential units and their respective occupants. While some dependency will exist on off-site sources for certain forms of nutrition (40% estimated), the system yields being planned and experimentally prototyped suggest an overall technological capability of generating greater than 100% of any single community's demonstrated demand for food, water, electricity, and for compostable waste.

The first ReGen Villages pilot community will be developed in the Oosterwold organic farm district of Almere, Netherlands, which is approximately a 30-minute from Amsterdam. The district designated by the Dutch government is intended to showcase off-grid capable housing and responsible neighborhood development planning that considers conservation and stewardship of natural areas and resources.
The ReGen Villages master plan maximizes whole ecosystem thinking to establish a prescribed balance between built and open spaces. Planning for resiliency is key for developing neighborhood-scale services that establish internal capacities for resource unit self-reliance despite external connectivity to municipal lifeline systems.
In conclusion, self-reliant and resilient communities such as ReGen Villages introduce new benefits to community members while reducing burdens for governments at all levels, alleviates demand for healthcare systems, reduce stress on banks, and decreases risk for insurance companies and pension funds alike. Above all, the ReGen Village concept establishes just and equitable residential housing solutions for increasing personal well-being while reducing exposure to impacts of climate-induced threats to lifeline resource systems.[4]

DETAILS

Client: Tesla & Regen Villages Holding B.V

Year: 2016

Starting construction: 2018

Design: EFFEKT

Project area surface: 15 500 m^2

Total built area: 135000 m^2

Residential units: 203

Budget (euro): 25 millions

House prices (euro): from 300 to 700 thousands

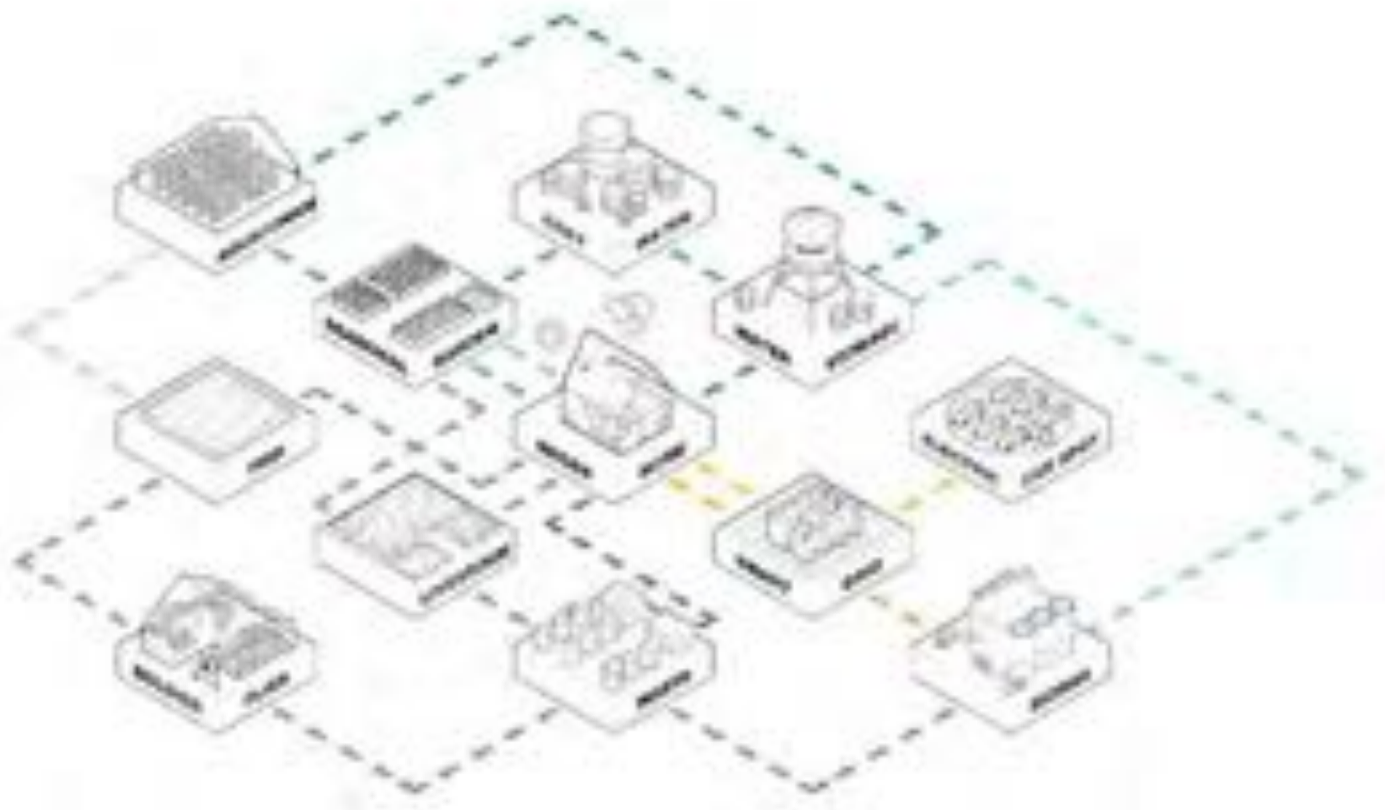
ENHANCE CIRCULARITY

ReGen Villages is all about applied technology. ReGen Villages is a Tech-Integrated and Regenerative Residential Real Estate Development.
Already existing technologies will be applied into an integrated community design, providing clean energy, water and food. All the urban agriculture technologies such as aquaponics, aeroponics or permaculture will be used in the ReGen village.

1. Water management
The word Regen does not only stand for "regenerative"; it has a double meaning. Indeed "regen" also means "rain" in Dutch and German. And actually, rainwater holds a prevalent role in this project. The ReGen system is found on the collection of the rainwater from the roofs of the homes. This collected rainwater will be stored and distributed afterward. The clean water from the water storage will be distributed to the aquaponics system, which is a water farming technique in which fish feces serve as fertilizer for the vegetable.

2. Waste recycling
The organic waste will become food for the livestock and the soldier flies. The flies will become in their turn, food for the fish, and the fish feces will be used to fertilize the plants in the aquaponics system. Manure from the livestock will become fertilizer for the seasonal gardens.
The organic waste as well as the potential unconsumed food will be transformed into biogas or used to feed the animals.

3. Renewable energy
In addition to the production of food, the Regen Village will produce its own energy, thanks to solar cells on the roofs of the homes. The latter will be linked to a smart grid, which will provide energy for the homes and allow the inhabitants to feed stored electricity back onto the grid when not needed. This surplus of energy in the smart grid will be used to charge electric cars.
The energy produced by the biogas facility will be added to the smart grid.



FOOD PRODUCTION

Those innovative technologies are thought to use less water and less land than the traditional agriculture and to produce more. In fact, the agricultural systems put in place in the ReGen Village, make it possible to produce 10 times more products than on a similar area with traditional agriculture, and above all, with 90% less water, thanks to the use of the urban agricultural technologies.

The clean water from the water storage will be distributed to the aquaponics system, which is a water farming technique in which fish feces serve as fertilizer for the vegetable. In addition to the aquatic ecosystem, aeroponics is another technique allowing to grow fruit and vegetable in the ReGen village. Aeroponics is a soil free culture system in which plants grow in an air or mist environment. In addition, grey water will be separated and filtered to be reused to irrigate the plants of the seasonal gardens.

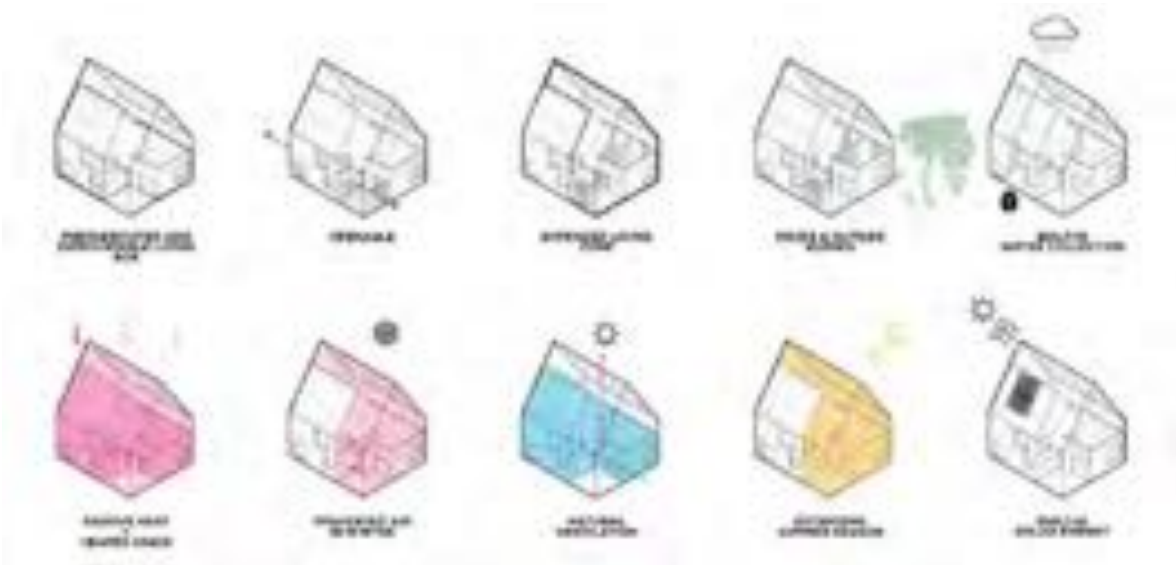
The purpose of the ReGen Village is to offer food security. **The whole ReGen system will be indeed built to grow organic food in abundance: fruit, vegetable, oleaginous, leguminous plants but also protein food, such as fish, eggs, chicken and other small animals rich in lipids and proteins.**

Ehrlich explained to Fast Company: “We don’t do lawns, we don’t do golf courses or tennis courts. That’s a good place to grow food, so we’re going to grow food there.”.

Indeed, food will be permanently produced, inside the vertical cultivations as a complement to the seasonal gardens and the farms. Moreover, families will be able to grow their own vegetable and fruit, all year long in connected greenhouses. Actually, each family’s house will have an attached greenhouse for growing personal crops. Together, the ReGen houses will form a “shared local ecosystem.” According to Ehrlich’s expectations, the village will produce enough fresh food to take care of 50-100% of the needs of its residents, he said to Business Insider. He specified that if there’s any excess food or energy gathered, that could be sold, and the profits could offset residents’ fees. The village’s farms and livestock will be managed and run by ReGen staff.

FOOD/PLANTS INTEGRATION

So the ReGen village relates not only to the construction of housings, but to the achievement of a whole system including waste, food, water and energy organization.
In this complete system, homes will obviously be totally designed for sustainable living. They will be energy positive homes. They will be powered by photovoltaic solar panels, and passive heating and cooling systems will take pressure off the electrical use of each house. In fact, the houses will be adjustable. Homes will be extendable in order to take advantage of the sunny weather in the summer and to preheat the air in winter. Thanks to these techniques along with the system of water collection and solar energy, homes will produce more energy than they will consume.



U03 - HomeFarm, Singapore - SPARK

INTRODUCTION

Homefarm is a conceptual proposal for the next generation of urban retirement housing. It presents a residential and commercial farming typology for Singapore that combines apartments and facilities focussed on but not exclusively senior living and vertical urban farming. The residents live in a high-density garden environment created by the vegetable farm, where they may find employment. SPARK's aim is to generate discussion about the potential that can emerge from the mixing of two typically separate realms. **The research-based design addresses two pressing challenges faced by Singapore: how the city-state might support a rapidly ageing society, and how it might enhance its food security 90% of which is currently imported**.[5]

SPARK unveils Home Farm – a concept for the next generation of retirementhousing for Singapore. The boldconceptual project proposes the combination of apartments and facilities for seniors with vertical urban farming.
The question of how to support and accommodate a rapidly ageing population confronts many nations in Asia. In Singapore, for example, a substantial demographic shift is underway. By 2030, one in five Singapore residents will be aged 65 years and over (up from 6 per cent in 1990). The swelling proportion of seniors will place significant demands on social, economic and infrastructural systems. Achieving a secure food supply for growing city populations is an equally pressing challenge for rapidly urbanising Asian nations. This challenge is keenly felt in Singapore, a small and fully urbanised city state without a hinterland.Currently, Singapore imports over 90 per cent of its food, and has in place strategies for the diversification of food sources and the boosting of local production through intensive agricultural technology.

The Home Farm concept allows seniors live in a garden environment created by a vegetable farm, where they may also find employment.The concept introduces verticalaquaponic farming and rooftop soil planting to the realm of high-density and flexible housing that has been designed to cater to the needs and preferences of seniors.
Residents may combat the financial stress that is often faced post-retirement by working part-time at the farm under the direction of a professional vertical farming implementation team. Facilities catered to the needs of an older population are provided in the lower levels of the development (and are also open to the public), while the housing is stacked above in a curvilinear terraced formation reminiscent of land contours.

DETAILS

Client: No client - concept design

Year: 2014

Starting construction: Concept proposal

Design: SPARK

Project area surface: Unknown

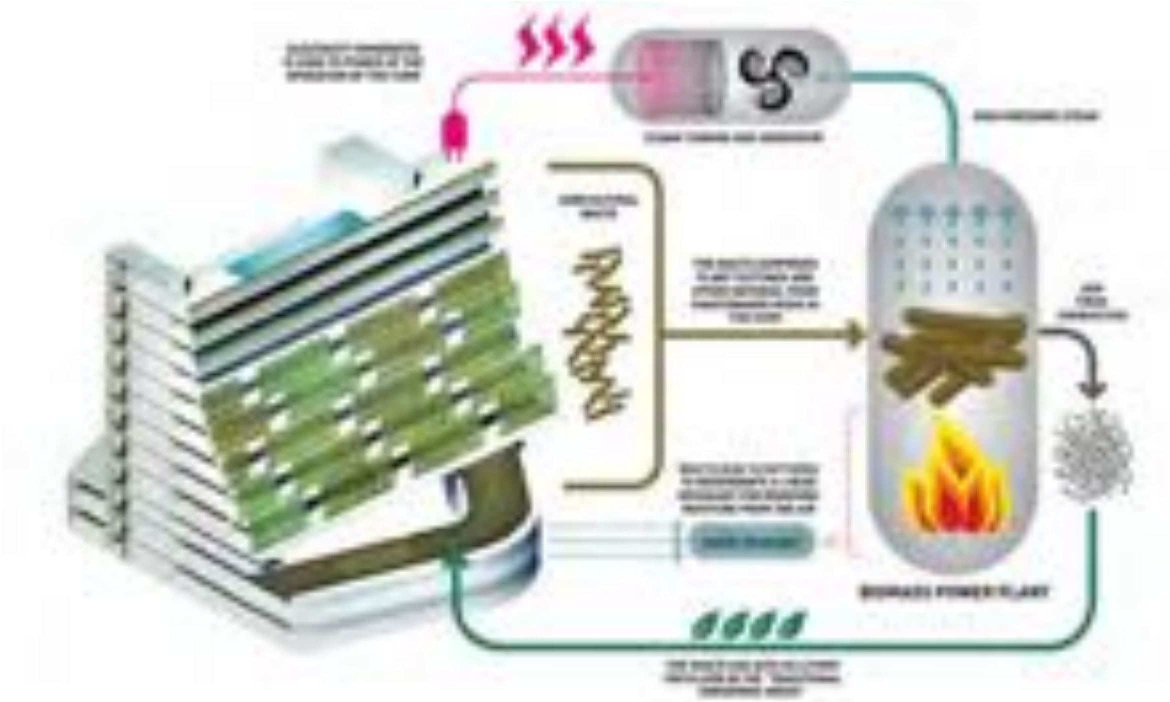
Total built area: Unknown

Residential units: 300

Extimated populaton: Unknown

ENHANCE CIRCULARITY[6]

The environmental sustainability and efficiency of Home Farm would be enhanced by proposed features such as the collection of rainwater for use in the aquaponic system, and the use of plant waste for energy production. The concept demonstrates SPARK's commitment to the goals of the Singapore Government's S$1.5 billion Sustainable Singapore Blueprint through the promotion of a vibrant, livable and sustainable city, and an active community.



FOOD PRODUCTION

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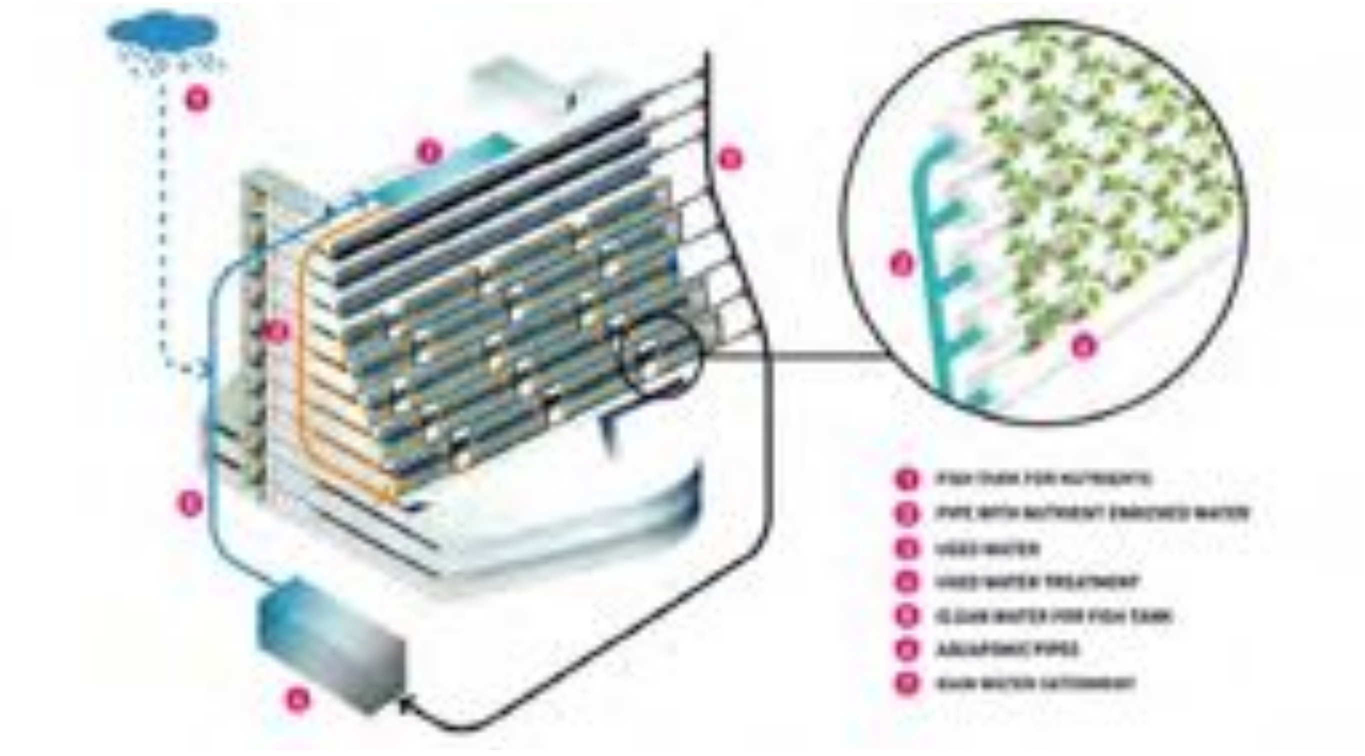
The gardening activity would offer numerous benefits beyond personal income generation, including community connectivity and the promotion of health. Simultaneously, beyond boosting the resiliency of Singapore's food supply, the production of food in the heart of the city could provide a platform for community education, help lower Singapore's high carbon footprint by closing the gap between producers and consumers, and contribute to the perpetuation of Singapore's 'City in a Garden' vision in a productive capacity.



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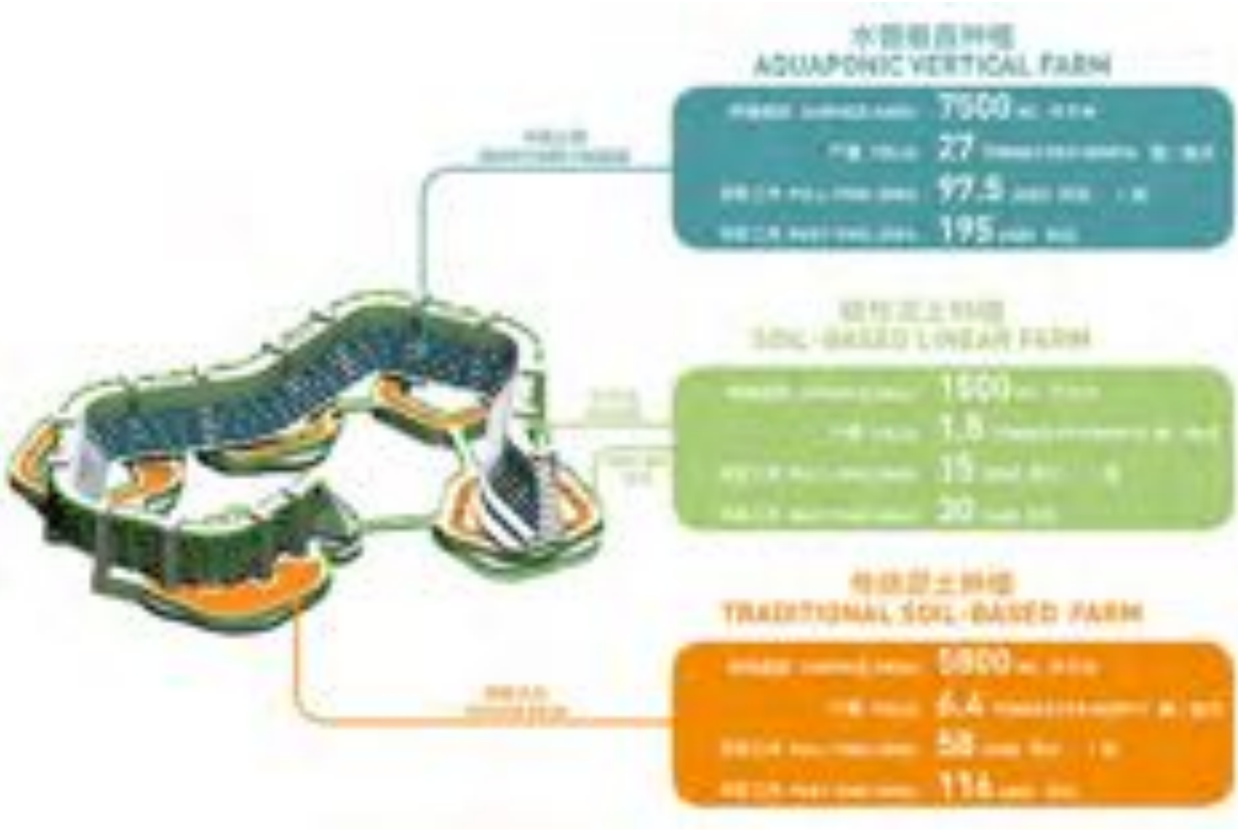
FOOD/PLANTS INTEGRATION



NC

INTRODUCTION

As the first combined agricultural and residential development in the Bay Area, the Santa Clara Agrihood is set to become a model for sustainable, urban design. Along with a 1.5 acre produce farm and community gathering center, this mixed-use development will provide housing for people of various ages and incomes; promoting a true community environment.

The project will be across from Westfield Valley Fair near San Jose on the former UC Davis agricultural research and development site. Westfield Valley Fair has been undergoing a $1.1B overhaul to create an entertainment and shopping destination

Offering a mixture of housing typologies, the 361 dwelling units are divided into townhouses, mixed-income apartments, and affordable senior and senior veteran housing. The apartment buildings are configured around large, open, landscaped courtyards above concrete parking podiums. Overall, the community is designed to support interaction, education, and farm to table living.

In addition to the agricultural area and residences, The Core Companies (developers of the project) will include 5,000 square feet of retail space. Pop-up vendors and special events are also planned for the development. A perk of living in the community will be to get food from the farm, and residents will be able to volunteer their time to tend to the crops.

Initial plans to turn the site into affordable housing in 2005 sparked push-back from community members who wanted to preserve its agricultural roots. The resulting controversy, plus a loss of state funding, eventually derailed that project.

With the new Agrihood plan, Core Companies sought to satisfy both residents who demand more housing in the community and those who prefer farmland. The idea is part of a nationwide trend that's especially popular with millennials — new housing developments increasingly are offering access to an urban farm, opportunities to work in the fields and unlimited fresh produce as perks of residency. A farm-based housing community called The Cannery opened in Davis in 2015, but the Santa Clara development will be the Bay Area's first.[8]

DETAILS

Client: Santa Clara city/Core companies

Year: 2016

Starting construction: Approved Feb, 2019

Design: Steinberg Hart

Project area surface: 2,4 ha

Total built area: 24300 m^2

Extimated populaton:

Residential units: 361

Number of social housing: 181

Garage & Parking spaces: 376

Urban Farm & Open Land: 0,7 ha

ENHANCE CIRCULARITY.

In the heart of Silicon Valley, Agrihood is preparing an innovative game-changing home project. The integration of the revolutionary urban farm, critical housing, and gathering space with the neighboring community will set a new standard for what's considered possible for future projects.

1. Urban Farming
One of the hallmarks of Agrihood is the Urban Farm. Connecting the project to Santa Clara's agricultural past, the farm will grow comfort and super foods, native fruits and berries, perennials, and drought tolerant plantings.

2. Transportation management
Core is pursuing GreenTRIP certification, or recognition of residential projects that apply strategies to reduce vehicle trips, excessive parking and greenhouse gases, while making transportation more affordable. GreenTRIP unleashes the power of smarter planning and shows a new paradigm for low-traffic development.

3. Solar power
Agrihood will be powered in part by renewable, emission-free solar power.

4. Biodiversity
The farm and gardens will be planted to maximize new habitats for local organisms, insects, and birds, and crops will be rotated to encourage natural soil restoration.

5. Transforming the suburbs
Agrihood will be a new intergenerational gathering place. Located on Winchester Avenue, the farm and outdoor space will be easily accessible to the whole community. Residents will also be a short trip away from the Santa Clara Senior Center, the International Swim Center, Central Park, and downtown San Jose.

6. Social& Physical Health
The farm's organic produce will provide a nourishing foundation, and the open spaces, walking paths, therapy gardens, and active lifestyle will inject new vitality in residents' lives.

FOOD PRODUCTION

The agricultural spaces are expected to be productive soon after residents arrive. Preparation and cultivation of the land begun shortly after the project's approval in January 2019, with delivery of hyper-local fruits, veggies, herbs, and nuts.

Three rotations of food crops are expected per year. **The farm will utilize organic and regenerative methods to obtain maximum yields while maintaining sustainable practices. Pesticides will be avoided by planting native hedgerows to enhance pollination and manage damaging insects.** Composting and vermicomposting programs will provide nutrients and pathogen protection to the soils and plants.

Food plants (as opposed to larger crops) will be grown throughout the property, not only in the farm plot. All available land will be cultivated as food forests, productive meadows and vertical farms to increase biodiversity, overall yield, and available habitat for native birds and insects.

Urban farming company Farmscape would manage the farm, which would be open to the public.
Novice farmers lease plots of farm land from the center at a discount, cultivate the land, sell their produce to local businesses and at farmer's markets, and keep the profits. The farmers also sell their fruit and vegetables once a week on The Cannery property, providing residents with easy access to everything from peppers to melons to leafy greens.

FOOD/PLANTS INTEGRATION

Five categories of potential crops have been chosen by the Core Companies and Farmscape:

Comfort foods:
tomatoes
zucchini
romaine lettuce
eggplant
onions
sweet potatoes

Superfoods:
kale
parsley
collard greens
chard

Native foods:
quailbush
strawberries
yerba buena
watercress
prickly pear
huckleberries

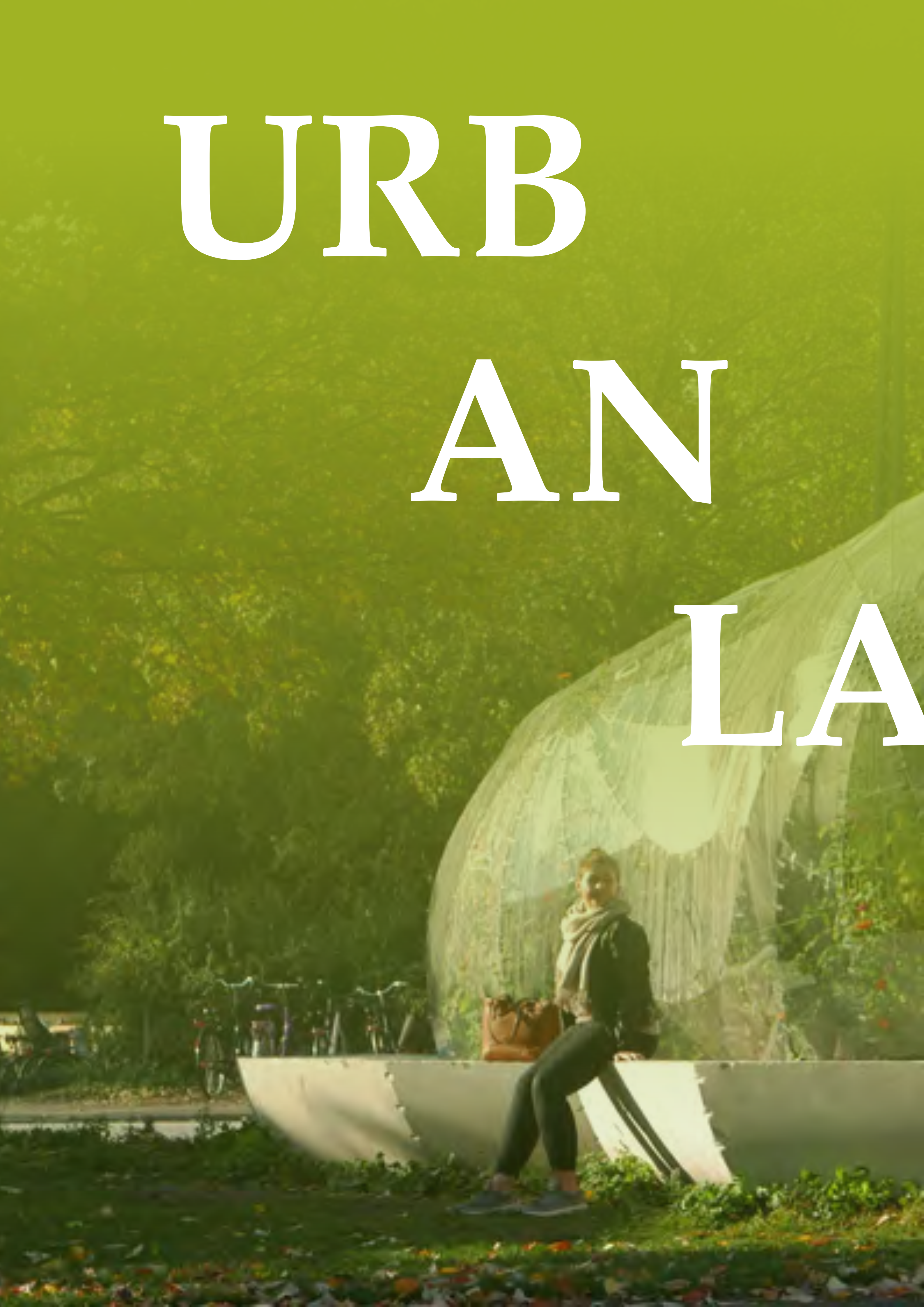
Perennials:
citrus trees
dwarf apple
pear
plum
apricot
almond
nectarine

Additionally, avocados, walnut and persimmons are being considered.

Berry vines and grapes for wine will cover fences, arbors and trellises.

Other perennials that may include sorrel, New Zealand spinach, golden berries, chives, chayote, malabar spinach, and sunchokes.

Drought tolerant plantings: olives
millet
sorghum
arugula
African basil
okra
cowpeas
mesquite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UI01 - UrbanFarmers BOX, Itinerant - Zurich based (SW)

INTRODUCTION

UrbanFarmersBOX is a 20sqm mobile urban farming unit used for events, teaching and explanation about sustainable urban food production and aquaponic.

The UF BOX is a small-scale food production unit that can be placed in backyards or on parking lots. The UFBOX uses aquaponic technology for the production of 60kg fresh fish and 120kg fresh vegetables per annum.

The UFBOX uses aquaponic technology developed by the Zurich University of Applied Sciences (ZHAW) and allows for ultra-local,
ultra-fresh vegetable and fish production without the use of herbicides or pesticides. The BOX is perfect for schools and small enterprises as a teaching tool.

The UFBOX is a fully functioning small-scale urban farm enabling the production of fresh food in a backyard or on a parking lot. The aquaculture system is housed in a retro-fitted cargo container and has a direct connection with a greenhouse on top of the container for production of plants. This is a perfect teaching unit for children in different learning stages. A vast variety of topics can be addressed: sustainability, ecosystems, agriculture, gardening, chemistry, food, cooking, aquaponics, plant health, fish health, food supply and population.

Aquaponics is an innovative method to grow fish (aquaculture) and vegetables (hydroponics) in a closed-loop water system with very high yield, low resource-intensity (particularly regarding water and fertilizer) and high-quality, zeroresidue products (no pesticide, fertilizer or antibiotics). UF's aquaponic technology has been developed since 2003 by UF co-founder Andreas Graber and his research group at the University of Applied Sciences Zurich.

The UFBOX can be used for a variety of projects, but has proved particularly successful as a hands-on classroom environment. The ZIS (Zurich International School) success using the UFBOX led to ZIS Adliswil (upper school) building their own UFSystem in their winter garden, so as to have a system available for the students to use at all times (students aged 14-16).

DETAILS

Client: Zurich University of Applied Sciences

Year: 2011

Design: Urban Farmers

Project dimensions: 20 m^2

Realization costs (euro): 25000

FOOD PRODUCTION

Due to the bankruptcy of the Urban Farmers it was not possible to retrieve any data concerning the food produced by the Urban Farmers BOX

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UI02 - Biotope, SHJwotks - Copenhagen (DK)

INTRODUCTION

SHJWork's projects emerge from the desire to and interest in creating a link between people and places. Their projects are often temporary and small scale architecture. "Biotope," a self-watering greenhouse and sculptural pavilion in the shape of a shell, is an experiment with a microcosm of plants and insects at an exposed and harsh place in the city. "In Greek, bios means 'life' and topos means 'place.' The project addresses these two words and their content," Jensen said.

The stage for the project is a small triangular greenery in the middle of an intersection with heavy traffic. A train station is nearby, and a three lane road together with a minor road is next to it. A lot of people walk, cycle or drive past this place every day. The edge of the bowl functions as a bench, and the inside life of the shell functions as an ever changing visual interest for the everyday passersby.

It is a temporary project standing for a three year period, and during these years there will be no maintenance or interference inside the shell. Neither is it possible for the public to access the shell. How the inside life with plants and insects will evolve over time is an experiment.

The sculptural and organic shape of the project is made specifically for the place. The shell mimics a simple shape of a primitive organism or bacteria. It lies with its "back" against the minor road and its "face" towards the most intense and energetic element: the three lane road.

DETAILS

Client/Supporters: Områdefornyelse Fuglekvarteret

Year: 2018

Design: SHJworks

Project dimensions: 84 m^3 (7x4x3 m)

Realization costs (euro): Unsaid

Materials: concrete basemen ; 4mm polycarbonate

FOOD PRODUCTION

Water
The bowl collects rainwater and leads it into the soil through small holes in the shell. In this way the plastic shell and the concrete bowl become a self-watering greenhouse. Sixty different seeds have been sown into the soil. Later as plants the majority of these seeds will attract insects. On the inside of the shell a beehive is attached. The bees have directly access to both the outside and the inside.

Living organism
By lying in this "posture" the project creates a small protected area between itself and an existing tree on the triangular greenery. The intention of mimicking a shape of a living organism is to explore if we humans can feel related to such a form. And if so, to see if an organic shape can be a "mediator" between humans and places.

The polycarbonate shell
The shell, made of clear 4 mm thick polycarbonate, acts as a film or a membrane. It protects the inside life from the outside harsh traffic and it creates a greenhouse effect. In favour of the plants the shell also holds back the moisture, vaporized from the rainwater and delivered by the bowl.

Maintenance
The temporary project — sited for a three year period — will receive no maintenance or interference. how the plants and insects — both inside and out — will evolve or thrive is an experiment left to experience over time.

Ecosystemic reviews
This was exactly the question that led to this project: to see how and if a fully enclosed natural microcosm could survive in a city, in those harsh and hostile conditions. As climate change could irreversibly change the world and our ecosystem as we know it, this study seeks to find ways of integrating nature in our lives, even in harsher environments: could it survive inside the homes of people in a global-warming-stricken world?

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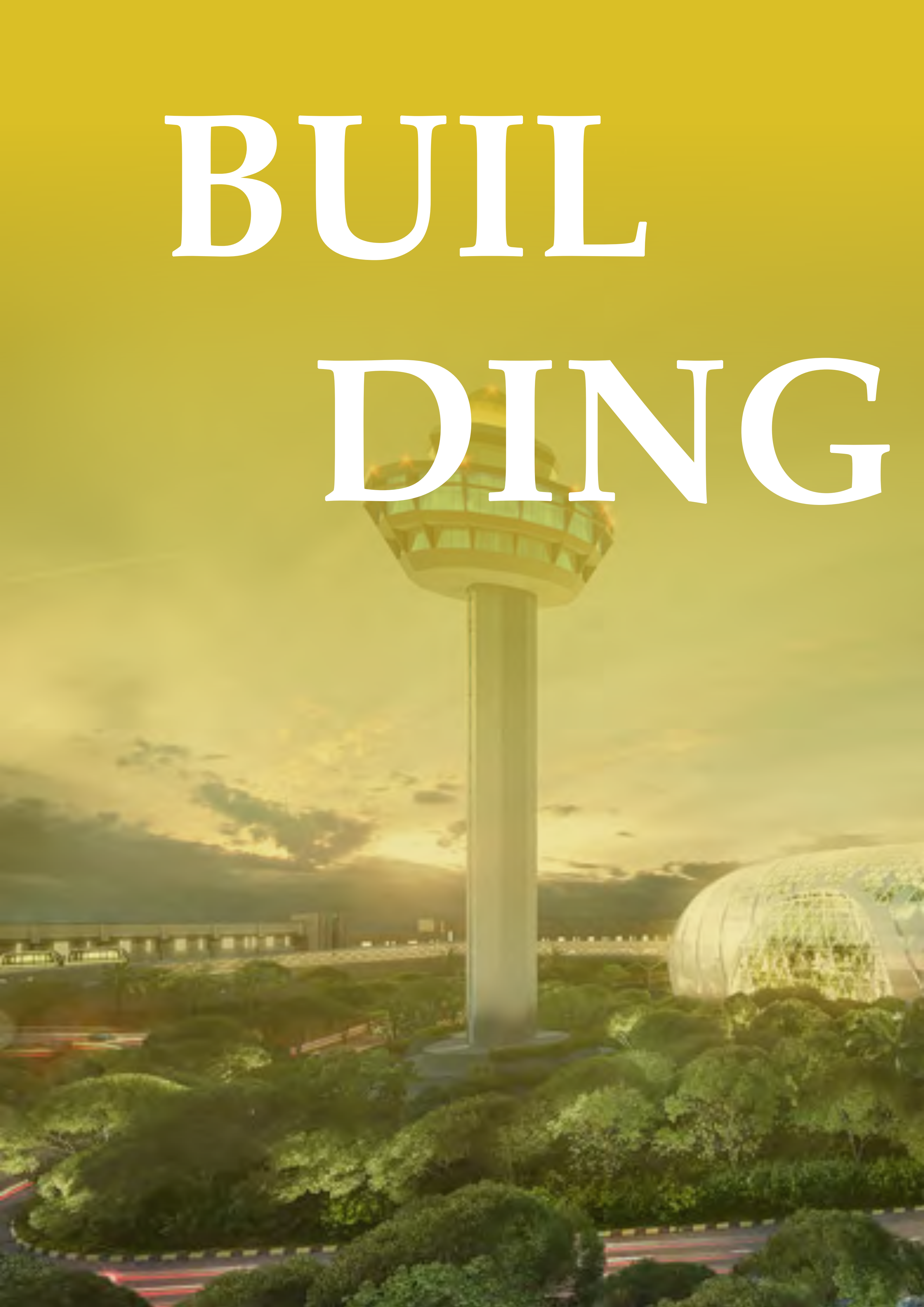

SCALE

INTRODUCTION

“Tropicalia” is a single-domed tropical greenhouse being built near northern France’s Opal Coast. It will span over 20 thousands square meter and be covered by a massive, air-filled plastic barrier to protect it from the outside world. Inside, lush vegetation will dominate the ground and visitors will travel along a walking path that measures nearly three-quarters of a mile long.contours.

The Metropolitan zone of the Opal Coast, an area of diverse landscapes and identity, enjoys a strategic geographic position. Located near London, Paris and Brussels, it is one of the main entry points to the continent forming a real European junction. 856,115 people live there, and every year, almost 24 million tourists come to visit the natural surroundings and cultural heritage of the region.
The Tropicalia project fits into the territorial, economic and tourist dynamic by providing everyone with a unique and original space, in the service of biodiversity, research and health.

The facility will serve scientists in various research efforts, and staff will be on hand to ensure the flora and fauna are living their best lives. At the same time, the building will host tourists who can dine at its upscale restaurant and stay in the built-in hotel.

“Tropicalia creates a harmonious world connecting man to an exotic natural, providing a constant temperature of 28°C in a region with notoriously poor weather. Whether it is an invitation into a dream, a grand voyage or an educational trip, Tropicalia is a place of discovery, amazement and ecological awareness.

This unique place will contain a diverse range of fauna and flora, butterflies, exotic flowers, hummingbirds, waterfalls, aquarium basins, fish, turtles, caimans and more. Beyond the eminently exotic interior world, the sensation of complete immersion is made possible with the innovative architectural approach.
The absence of any load-bearing columns that would disrupt the view or introduce artificiality, coupled with the natural treatment of the perimeter vegetal wall that allows only a view up to the sky from within, visitors have the sensation of a space disconnected from the world outside.
From the exterior, the architecture merges with the landscape: the building is partially set in the ground, diminishing its height and impact. From a distant view, the structure rises like a gentle hill in its natural landscape.

A project such as Tropicalia implies an increased resourcefulness and a serious sustainable approach. Therefore, the roof structure implemented is composed by EFTE pressurized air cushions within an aluminum frame.”[1] (http://www.caau.fr/project/tropicalia)

DETAILS

Client: Opale Tropical Concept

Starting / Ending construction: 2019 / 2021

Design: Coldefy & Associates

Project area surface: 20 000 m^2

Costs (euro): 50 millions

Expected visitors (per year): 500 000

ENHANCE CIRCULARITY

"Our main objective for the Tropicalia project is to optimise the energetic efficiency of the dome while keeping to a minimum the impact on the surrounding environment", explains Denis Bobillier, the Technical Director of Major Projects at Dalkia.

"Consequently, we designed a double dome producing its own energy, capable of maintaining a tropical atmosphere no matter the external climate because one of the main challenges of greenhouse performance is its heating system."

Thanks to the double layer of ETFE in the roof and innovations made by the Dunkirk firm, Terraotherm – a specialist in thermic engineering - Opale Tropical Concept, the architect firm of Coldefy & Associés and Dalkia have come up with a tropical greenhouse equipped with a system to keep the carbon footprint to a minimum.

Tropicalia will apply a unique method in recycling thermic energy produced by the greenhouse effect. "**In summer or in very fine weather, the double dome will raise a layer of air to a high temperature which will transfer the air calories to the water by means of an exchange device, so heating up the water in the lakes. That stored heat can then be used to generate warmth at night or during colder periods.** The immense surface of the dome will also allow recovery of rainwater to nourish the plants throughout the year."

"This double insulating dome will protect the tropical ecosystem in the summer and maintain the necessary temperature during the winter," concludes Denis Bobillier. The temperature will always be kept between 26 and 28 degrees Celsius.

The fact that the greenhouse is partially underground will boost insulation. "**The excess heat can then be directly used, stored or even redistributed to our neighbours in the framework of a private heating network or "smart grid"**.

ARCHITECTURAL SOLUTIONS

Tropicalia will be topped by a "double dome", formed by a metallic structure bearing ETFE strips, 60m long and 4m wide. A synthetic mineral membrane in pressurised "cushions" makes up the outside layer of the dome creating the initial thermic insulation, which nevertheless allows passage of the total light spectrum. A third layer of ETFE will be deployed under the bearing structure so as to accumulate the heat produced by the overall greenhouse effect.

This will be created to house a complete universe of plants and animals in perfect harmony. The dome will be home to butterflies, honey- and fruit-eating birds, fish and reptiles and a vast botanical collection of flowering plants, orchids and a forest of tropical trees.

This unique concept built on several levels will contain:

- a tropical forest
- a beach-zone for rays and turtles
- a tactile pond for children
- a huge lake for large Amazonian fish
- a pedestrian circuit of more than 1 km

The quality of the inside space is guaranteed by its unique volume, unbroken
by any vertical structure. The greenhouse will be enclosed by extensive planted areas to optimise the insulation of the whole zone, and especially to enable a more complete immersion into the tropical environment. The visitor's journey will start at the high end of the greenhouse via a gangway that traverses the canopy of a forest. The path then drops down and slowly follows around a "mountain", wending its way between cascades and spectacular waterfalls.

FOOD/PLANTS INTEGRATION

The Fauna

Butteflies

Tropicalia will be home to almost 80 species of lepidopteran, a permanent presence of 8,000 butterflies living in complete freedom. Thanks to the transmission of UV rays through the dome and the vast volume of the greenhouse, the butterflies will adopt a totally natural behaviour. Approximately 1,000 chrysalides will arrive every week in the greenhouse and a scientific breeding programme will be set up to help perfect our understanding of the entomological world.

Honey- and fruit-eating birds

As there will be butterflies in the greenhouse, only honey- and fruit-eating birds will be kept there. Tropicalia will be one of the only places open to the public in Europe where visitors can admire these birds. In all, ten or so species will be found there, including turacos and humming birds. A scientific research programme will be developed to find new solutions to help protect these species more efficiently in the wild.

Fish and reptiles

Three lakes are being planned in the Tropicalia dome, one of each hosting different species of tropical fish: i) Potamotrygon, ii) Koi carps (in the tactile lake where you can touch the fishes), iii) Amazonian fishes (15 species in total).

The Flora

The careful selection of plant species in Tropicalia will allow for an ecosystem in harmony with all the animals present. There will be three families of plants.

An area of 800m2 will be reserved for orchids. There will also be a forest, specially laid out with trees acclimatised in Holland, measuring between 12 and 15m. Different species such as coffee bushes, mango trees, cacao-trees or bananas will enable visitors to see where the products they use all year long come from. Specific "auxiliary" insects will be introduced inside the greenhouse to eliminate the various parasites. That is to demonstrate to visitors how alternative methods can be used to respect the environment.

B02 - The FarmHouse, Precht - No location

INTRODUCTION

"In the next 50 years more food will be consumed than in the last 10.000 years combined and 80% will be eaten in cities. It is clear that we need to find an ecological alternative to our current food system. What and where we grow and eat. Topics like organic agriculture, clean meat, social sourcing and 'farm to table' will be key elements of this change. That means that our urban areas need to become part of an organic loop with the countryside to feed our population and provide food security for cities.
If food is grown within the region, the supply chain and the use of packaging gets shortened. Stacked gardens reduce the need to convert forests, savannahs and mangroves and allows used farmland to naturally restore itself. Vertical farms can produce a higher ratio of crop per planted area. The indoor climate of greenhouses protect the food against varying weather conditions and offers different eco-systems for different plants."[2] (https://www.precht.at/the-farmhouse/)

Architecture studio Precht has developed a concept for modular housing where residents produce their own food in vertical farms.

Architects Fei and Chris Precht, who is also the co-founder of architecture studio of Penda, developed The Farmhouse as a way to reconnect people in cities with agriculture and help them live in a more sustainable way.

The conceptual modular system would allow people to grow food in residential tower blocks to eat or share with their local community.

"I think we miss this physical and mental connection with nature and this project could be a catalyst to reconnect ourselves with the life-cycle of our environment," said Chris Precht.

DETAILS

Client: Not specified

Starting / Ending construction: None

Design: Studio Precht

Project area surface: Variable due to the modular nature of the project

Costs (euro): Not Specified

Number of inhabitants: Not specified

ENHANCE CIRCULARITY

The Farm

"Our Farmhouse runs on an organic life-cycle of byproducts inside the building, where one processes output is another processes input: Buildings create already a large amount of heat, which can be reused for plants like potatoes, nuts or beans to grow. A water-treatment system filters rain- and greywater, enriches it with nutrients and cycles it back to the greenhouses. The food waste can be locally collected in the buildings basement, turned into compost and reused to grow more food."

"This process of food production becomes visible," says Precht. "It reenters the centre of our cites and the centres of our minds. Food is an important part of our daily life and I see 'the Farmhouse' as an educational statement that it's no longer a mystery where our food comes from and how it lands on our table."

(*Texts provided by the architects*)

ARCHITECTURAL SOLUTIONS

The Farmhouse consists of a fully modular building system, which is prefabricated offsite and flat-packed delivered by trucks. Prefabrication of a modular building kit shortens the time for construction and its affect on the surrounding. The building system is based on structural clarity of traditional A-Frame houses and connects to a diagrid that runs the loads through the building. Each wall of the frame exists of 3 layers. An inside layer with finishes, electricity and pipes, a middle layer with structure and insulation and an outside layer with gardening elements and water supply.

For single-family structures, this systems gives a tool to home-owners to design their own place, based on the needs and the demands to living and farming. Structural and gardening elements, waste management units, water treatment, hydroponics and solar systems can be selected from a catalog of modules and offers a certain flexibility for various layouts. Single-family users would be able to build their own homes using as many modules as they chose, or taller housing blocks could be formed by arranging the A-frames into stacked duplexes.

The hands-on approach of the DIY movement played a big role in the design. Not only for the gardening part of the building, but also for its construction. This method allows owners to self-construct their tiny houses based on their chosen layout. Architecture that is home-built with food that is home-grown.

Taller structures are assembled as duplex-sized A-frames, which provide a large open space on the first floor for a living-room and kitchen and a tent-like space on the second floor for bedrooms and bathrooms. The angled walls give space for gardening on their outside and create a V-shaped buffer zone between the apartments. This also lets natural ventilation and natural light into the building. The building invokes a direct connection with a natural surrounding, that stands apart from the concrete landscape of our cities. A tent that is surrounded by nature. A Yin&Yang of colorful gardens and healthy interiors.

Prefabricated A-frame housing modules made from cross-laminated timber (CLT) would be stacked to provide flexible living spaces.

CLT is more sustainable than other low-cost building materials such as concrete because it locks in the carbon absorbed by the trees that were grown to make it.

Each of the module's wall would be made of three layers. An inner layer, facing the home interior, would hold the electricity and pipes with the surface finishes.

A layer of structure and insulation would form the middle layer, and on the outside layer would hold all the gardening elements and a water supply.

Different modules would have different types of external systems, such as hydroponic units for growing without soil, waste management systems, or solar panels to harness sustainable electricity.

FOOD/PLANTS INTEGRATION

The Concept

“The gardens can be used privately for residents to grow their own food, or as a collaborative effort to plant vegetables and herbs for a wider community. After the harvest, the food can be shared or sold at an indoor farmers market on the lower floors of the building. Educational classes, a root cellar and compost units round up the idea of an ecological loop within one building.”

MISSING INFORMATIONS ON THE CROPS AND THE PLANTS CHOSEN BY STUDIO PRECHT AS THE PROJECT IS PURELLY CONCEPTUAL

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INTRODUCTION

"The office building in the center of Oberhausen combines the diverse functions of a public administrative building and rooftop garden in a new way, integrating features of both typologies. The tension between the physicality of the brick building and the delicate lightness of the greenhouse creates a new identity that affects the urban context of the Altmarkt, an important location in the city." (*Text provided by the architects*)

The new administrative center on the Oberhausen Altmarkt is an urban planning strategy to invigorate the Alt-Oberhausen inner city center. On top of the building the municipality invested in the construction of an integrated greenhouse, managed by ALTMAKRTgartens. Here, the urban farming principles proposed by inFARMING® allow the Oberhausen-based Fraunhofer Institute for Environmental, Safety and Energy Technology to carry on research on urban food production.

The puspose of adding the building-integrated roof greenhouse into the new construction process of this public administration building is to create a lively, open, diverse and innovative hub. Here, different pratices and experises worked together to connect working and production spaces. The global architecture design was given to Kuehn Malvezzi who won the municiplaity pubic tender. The Greenhouse structure and disposizion was then entrusted to Haas Architekten. Eventually, the management of the greenhouse is used by Oberhausen-based Fraunhofer Institute for Environmental, Safety and Energy Technology as a research institution.

DETAILS

Commission: Oberhausener Gebäudemanagement gmbh

Ending construction: 2019

Design: Kuehn Malvezzi

Greenhouse design: Haas Architekten

Project area surface: 7839 m^2 of which 1000+ m^2 GH

ENHANCE CIRCULARITY

The combination of greenhouse and office has been used to create a circular system of services, where **warm air extracted from the workspaces is fed into the greenhouse** and wastewater collected from the building's sinks and toilets is used in the vertical garden.

The ALTMARKTgarten is currently focusing on the **optimization of water consumption**. The usable area of the roof greenhouse is more than 1 000 m², of which the Fraunhofer UMSICHT will operate 160 m² of research and development.

The Fraunhofer Institute for Environmental, Safety and Energy Technology is investing now how far water flows or waste heat from the building can be used to grow the plants.

The waste heat is led from the job center directly into the R & D area. 'Gray water', water from showers and hand wash basins, is processed in the cellar. On the one hand, so that it can be used inside the building, on the other hand to test the use for irrigation in the R & D area. Exposure is also a focus of the researchers, because certain lighting scenarios can positively influence plant growth and plant quality.

The inFARMING® concept minimizes transport routes between cultivation and consumption by locally marketing the rooftop vegetables in urban areas. Using resources optimally and closing material cycles can reduce energy consumption, carbon emissions and waste.

Population was onstantly informed about the project during its development, and now, there is also a central information pavilion in the city center.

A survey of the citizens of Oberhausen revealed that the majority view the project positively. 80 percent of respondents plan to visit the rooftop greenhouse, 70 percent see it as an asset to the city center.

ARCHITECTURAL SOLUTIONS

A steel-framed vertical garden cuts through the centre of the administrative brick building block in Oberhausen, Germany, topped by a translucent urban greenhouse for agricultural research with a zigzagging roofline.

The building combines a five-storey job centre at its lower levels with a greenhouse and spaces for the Fraunhofer Institute for Environmental Safety and Technology (UMSICHT) above. The two elements are not divided and conntected with a vertical garden courtyard at the centre of the brick block.

The brick base of the building is designed to blend in with the historic surroundings of the city, while the translucent glass form of the greenhouse and the lightweight steel structure of the courtyard creates a **new tensions between the two architctonic entities**.

"The specificity of this important urban location results form the tension between the physicality of the brick building and the filigree lightness of the greenhouse on the rooftop" said the architect.

The plan is caracherized by a U-shaped form, the presenting a flat brick facade to the road facing north, but opens up to the south to reveal a skeletal steel structure. Vertical gardens and plants are integrated into the transparent facade, accompanyng the visitors from the bottom to the top greenhouse.

"A seemingly floating surface of galvanised steel grids makes it easy to walk over the bed to the first staircase. New plants are added to the garden on each floor, and a balcony at the end of the walk offers a view over the town and market square," said the Malvezzi.

Inside, high ceilings create generous spaces in which material finishes and services have been left exposed, with the intention of the warehouse-like rooms being flexible for **potential future transformation** into apartments.

On the fourth floor is a seminar and conference space, as well as additional areas for events and training.

FOOD/PLANTS INTEGRATION

The vertical garden — which comprises hardy climbing plants, like the crimson glory vine and common hop, on a galvanized steel structure — are complemented with a bed of small shrubs and ground cover plantings.

Fruit, vegetables and the like will be cultivated in three different climate zones. Also, research will be carried out in a fourth climate zone.

The individual zones of the roof greenhouse can be controlled separately, depending on the need for temperature and humidity of the plants.

Another special feature is that the production-oriented areas use different cultivation systems. In addition to the ebb-tide tables, which supply plants with time-controlled flooding with water and nutrients, they are grown in UV-stable growbags.

Fertilization and addition of water take place here by drip irrigation; excess water is returned through a channel system in the water cycle.

In another culture system, the plants are on culture plates (floats / pontoons) in swimming ponds. Recesses in the plates provide support and allow direct rooting in the water.

All culturing systems used are hydroponic. The plants are nourished by an aqueous solution. A fertilizer machine controls the nutrient supply individually adapted to plants and cultivation system.

B04 - The Greenhouse Restaurant, cepezed - Utrecht (NL)

INTRODUCTION

The Green House, located next to Utrecht central station, includes different functions as: a restaurant for 150 people, flexible meeting rooms, an urban farm, an outside terrace and an outside edible garden that are distributed over two floors. Makers of Sustainable Spaces (MOSS) and HRBS designed and developed the urban farm and outside herbs garden.

In 2014 cepezed was commissioned to make a modern government office from the former Knoopkazerne on the Croeselaan in Utrecht. The Central Government Real Estate Company also requested a solution for the space between the Knoopkazerne and the adjacent head office of Rabobank.

As a definitive destination for this location will be decided in fifteen years, probaby an apartments tower, a temporary interpretation was sought that could make the area that would otherwise remain vacant, more lively. Cepezed developed a plan in which both the function and the architecture are based on circularity.

On the top floor of the building thesi a publicly accessible urban farm - a greenhouse of 80m2 that is clearly visible from the street side.

Here is where vegetables and herbs are harvested to be processed in the meals of The Green House. Harvesting right on site, omitting packaging and refrigeration makes it fresh and sustainable.

DETAILS

Commission: Central Government Real Estate Company

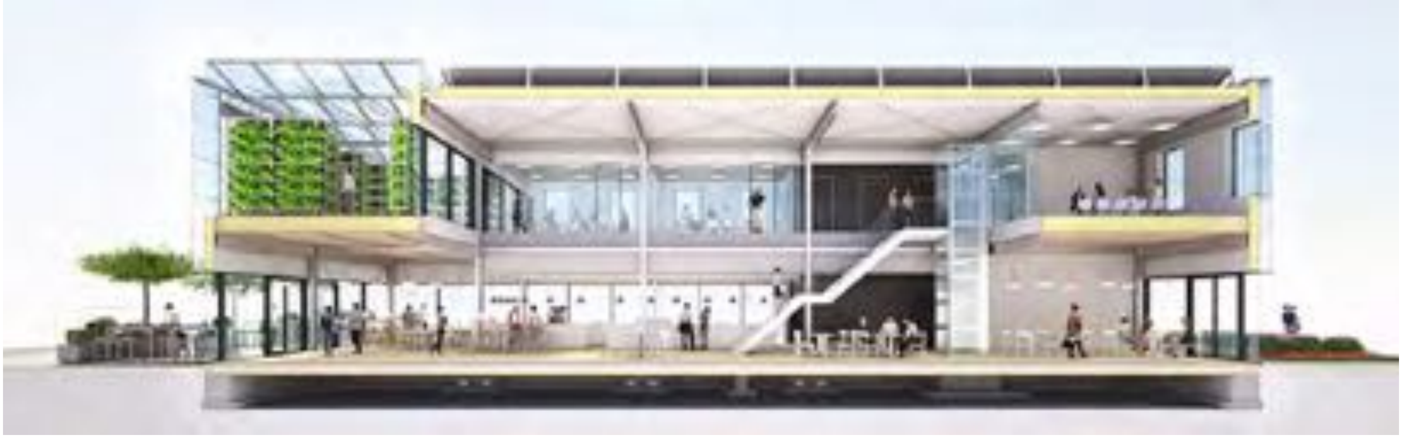
Ending construction: 2018

Design: cepezed

Greenhouse management: HRBS

Project area surface: 680m^2 of which 80m^2 greenhouse

Restatuant seats: 150



ENHANCE CIRCULARITY

In accordance with the principles of circularity, the building (including the foundation of prefab concrete blocks) is completely dismountable. In fifteen years it can be built up elsewhere.

The aim was also to implement reusable materials as much as possible. The two-story pavilion is designed as a generic building kit with a removable steel frame made of galvanized profiles. The dimensions are derived from those of the smoke glass facade panels of the former Knoopkazerne; these have been re-used for the second skin and the greenhouse of the pavilion.

Also for the design of the restaurant, a large part of the interiors has been found and the new furniture were built from recycled materials only.

ARCHITECTURAL SOLUTIONS

When you enter The Green House, its peculiar design immediately catch the eye. The first thing tha appears to the visitors' eyes is the upper floor greenhouse with herbs and vegetables. On the right, an entire interior wall bedecked with tropical plants, and on the left the open kitchen where hte huge "Zaai plant eet lekker!" slogan decorate the wall (Translate: Sow, Plant, Enjoy your food).

At the groundfloor, the restaurant hosts several tables where evertything comes from recycled materlias. A wooden staircase brings the guests to the upper floor where they can see the offices spaces and take a look at the HRBS greenhouse, where food cooked in the downstair kitchen is served. The access to the greenhouse and the offices is restricted, but the architects decided to show them anyways to fully integrate different activities within the buildnig.

A vertical farming greenhouse, of 80 square meters, is located on the first floor next to the meeting rooms. Here vegetables and herbs are grown for the restaurant kitchen. A vide in the pavilion makes the publicly accessible greenhouse visible from the restaurant below. The large green wall also contributes significantly to the experience of The Green House.

On the outside, the large glass façade panels all originate from the pre-existing building. "The panel size even determined the building's dimensions" says Ronald Schleurholts of Cepezed. "Everything has remained precisely as it was and even the corners are formed using complete panels, so that we didn't have to cut them".

Inside, street clinkers from an old quay in Tiel replace the classic ground floor that has been poured. They are located on a compacted sand bed with underfloor heating. The first floor consists of prefabricated wooden elements. In view of the acoustics in the restaurant, the sub-plating is perforated and the elements are filled with insulation.

For the roof, the choice fell on a light steel sheet that was also perforated and filled with insulation. With a glass curtain wall, the plinth of the pavilion is completely transparent. For the closed parts of the façade on the first floor, prefabricated timber frame panels were used. These are 100% recyclable and (H) CFC-free.

The roof of the pavilion is filled with solar panels. The Green House is the first to have an ac-plug-free kitchen in which food is prepared without electricity but with energy-efficient ovens fired with renewable fuels.

FOOD/PLANTS INTEGRATION

HRBS is the company entrusted in the maintanance and operational managment of the 80 sm greenhouse located on the first floor of The Greenhouse Restaurant.

They will provide new trays of plants every time it is needed, and let them grow in the top floor greenhouse. The Greenhouse Restaurant counts more than 300 trays.

The growing methods used in this projects is what the company calls HRBS TRAY CART which can each contain 9 to 18 different plant species such as: basil, lattuce, chervil, chives, choco mint, coriander, lemon balm, moroccan mint, oregano, parsley, rosemary, sage, swiss mint, thyme and edible flowers.

The dimensions of the Tray are:

Height | 2000 mm
Width | 1350 mm
Depth | 565 mm

Its design includes:

Steel frames (powder coated steel)
Wheels
Water basin
LED Grow-light

B05 - Mochi Restaurant, Tres Birds - Denver (US)

INTRODUCTION

The Mochi restaurant is part of the S. Park redevelopment, a one square block in the Curtis Park Neighborhood in Denver Colorado. The goal of this dense, mixed-use multifamily residential development was to create workforce housing in central Denver that encourages the homeowners to lead a dignified sustainable lifestyle. Located at 26th and Lawrence, the site marks a transition zone between commercial and residential streetscapes.

The project aims to honor the neighborhood context through materiality, form, and rhythm, while increasing density through multi-family living. The homes vary in scale from 37 sm studios to three-story three-bedroom units. Brick of three different colors clad the façades, which are broken up with a 50′ cadence to evoke the scale of houses in the surrounding residential neighborhood.

Much of the brick at S. Park is reclaimed. The various patterns and uses of brick create interest and texture, as well as support specific functions. Strategically omitted bricks at balconies and outdoor stairs allow light to pass through as well as a view out. Turned bricks on the ground level facades encourage greenery to climb.

A ground level urban garden occupies the southeastern corner, adjacent to a 650 sm elevated greenhouse, which captures enough natural light to grow microgreens throughout the year. The park is home to an outdoor kitchen and dining area, a grass lawn with porch swings, a fully planted storm water runnel and detention pond, and tall poles supporting homes for birds and bats.

(*Texts provided by the architects on their website*)

DETAILS

Commission: Westfield Co. Inc. & Mochi Franchise

Ending construction: 2018

Design: Tres Bird Workshop

Restaurant area surface: 650 m^2 650 m^2 of GH

ENHANCE CIRCULARITY

The greenhouse utilizes passive heating and cooling strategies, with automatic venting and thermal blankets that stretch across the interior on cooler nights. This low energy, high tech glass building has a strong presence that carries the corner of the site.

Uchi, the restaurant below the greenhouse, is one of the main buyers of the produce produced and allows for a visually connected ‘farm to table’ experience.

A 200-kwh rooftop photovoltaic array offsets the site’s energy use, which is primarily electric. The project utilizes high-efficiency LED lighting inside and out, High performing low-E windows, low VOC interior paint, and advanced insulation levels.

Solar gain is contained in the greenhouse, the large concrete slab acting as thermal mass, regulating temperatures above and below. Sunlight fuels plant life, plant life fuels human life. The relationship is functional and visual.

ARCHITECTURAL SOLUTIONS

US firm Tres Birds Workshop has topped a Japanese restaurant in Denver, Colorado with a greenhouse featuring soil-free growing towers.

The building is located within a block-long, mixed-use development called S*Park, short for Sustainability Park.

Local studio Tres Birds Workshop designed the entire development – which encompasses housing, commercial space and urban farming – near the downtown area of the Colorado city.

For one corner of the site, the team created a two-story building to house a street-level restaurant and an upper-level greenhouse.

Rectangular in plan, the building consists of a relatively solid base made of brick and concrete. Up above, a fully glazed volume is topped with a multi-gable roof, giving the building a distinctive look.

"Uchi creates food with fresh ingredients in ways that defy expectations," said the architects. "The design intent was to support this mission through the programme of the building and the sensory experience of the space."

On the exterior, the restaurant is announced via a large, backlit sign. Visitors step into an L-shaped dining area that is organised around a central sushi counter and bar. The dining area features two rooms with different atmospheres – one is light and warm, while the other makes use of darker tones. Wooden screens help delineate specific zones.

Like other parts of the S*Park development, the architects sought to use common materials in an unexpected way. One of the eatery's most distinctive features is its southern wall, which is composed of reclaimed red bricks and custom-made crystal blocks.

"These crystal bricks transfer light and energy, connecting the comfortable interior to the distant cityscape and the eye of the passerby to the warm light within," the studio said.

The dining furniture consists of dark wooden chairs and tables, and booths with tan upholstery. Concrete flooring lends an industrial feel that is countered by the ample use of wood throughout the eatery.

FOOD/PLANTS INTEGRATION

Right up above the restaurant, the Tres Birds team created a 7,000-square-foot (650-square-metre) greenhouse that "supplies the kitchen with the freshest organic greens available throughout the year".

Managed by Altius Farms, the growing area features white, aeroponic towers that require no soil. The plants – which include lettuce, herbs and edible flowers – are regularly misted with nutrient-laden water. This is one of the largest vertical aeroponic rooftop gardens in the country.

Plants here grow out from vertical columns, not up from pots or beds. The plants' root systems are housed in ports of spongy, inorganic growing mediums, which are popped into little openings in the columns. A gravity-fed, automated irrigation system pushes a pH-balanced, nutrient-fortified mist through the columns for three minutes at a time in 15-minute intervals, keeping the plants' air-suspended roots moist.

The greenhouse itself was designed to recognize the plants needs by pooling the environment. Sensors around the greenhouse cue the processing system to turn on fans or heaters, open up roof and side vents to adjust the humidity and temperatures to make the greenhouse the perfect environment for growing leafy greens. The greenhouse also provides a controlled environment for their plants to grow. Altius Farms has a separate water system and a controlled environment that is not affected by the state of surrounding farms.

The production system is characterized by 340 columns, each 2.5 meters, where green rosettes of butter lettuce, neon mustard frills, ruffles of baby red Russian kale, and lily-pad-like nasturtium are cultivated.

Altius' list of clients is not just limited to The Uchi restarutan downstairs, but feeds othe local restaurants like Il Posto, Butcher's Bistro, and Marczyk Fine Foods.

ROOF TO GARD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RG01 - Sunwork centre, K+C - Manhattan (NY)

INTRODUCTION

The Sunworks Center at PS 333, The Manhattan School for Children, is a rooftop environmental education greenhouse, producing hydroponically grown vegetables on the Upper West Side. This is the first greenhouse to be part of the **The Greenhouse Project** (http://nysunworks.org/thegreenhouseproject) - a vision of a group of parents and educators to create environmental science laboratories on the rooftops of NYC's public schools.

Founded in the early 1990s through the efforts of parents and teachers in New York City's Community School District 3, The Manhattan School for Children is a public school with students from diverse backgrounds and cultures. Along with partner NY Sun Works, MSC is developing a curriculum that will act as a prototype for other public schools and has funds set aside for a full-time environmental science teacher.

The lab accommodates up to 35 kids and is available every day of the school year. Students experience science through interactive technologies such as hydroponic vegetable farming, solar panels, a rainwater catchment system, a weather station, worm composting, and a kitchen corner.

A cost-effective public / private partnership between the school, parents, and outside funders, the greenhouse classroom has been built directly on an existing 3rd floor roof with only minor modifications to the building. As the first rooftop environmental science lab in a New York City public school, the greenhouse will grow 8,000 pounds of produce annually.

DETAILS

Client/Developer: New York City Department of Education

Ending construction: 2010

Design: Kiss+Cathcart Architecture

Project area surface: 150 m^2

Costs (USD): 550 000

Maximum capacity (student per day): 35

ENHANCE CIRCULARITY

The rooftop laboratory at MSC will hold a touch-screen display of energy and weather systems which will aid students' understanding in the relationship between energy, weather, and plant growth, through monitoring humidity, solar radiation, and carbon dioxide within and outside the greenhouse.

Building-integrated photovoltaic cells will power fans in the classrooms and will educate students in physics and renewable forms of energy.

A rainwater capture system will provide water for evaporative cooling and help supply the 100 gallons of water needed each day to irrigate the greenhouse's crops. The evaporative cooling system will aid students understanding on how to control the climate within the greenhouse, naturally.

Green energy features
Solar panels + PV panels

Energy efficiency features
Good air sealing.
Retractable heat blanket
Twinwall polycaronate roof

Set back temperatures at night and weekends.

Electric heat pump that uses main building condenser unit

Water conservation
Rainwater collection system estimated to collect 40,000 gallons annually.

FOOD/PLANTS INTEGRATION

The greenhouse classeroom uses hydroponic systems that are strategically placed to receive the best lightining and maximize food production.

Plans to include a Nutrient Film Technique (NFT) system will show students exactly what a plant needs to survive and can produce up to 75 heads of lettuce a week, ideal for nutrient-filled lunches. The plant production isncflueds lettuce and leafy green herbs cause they are ready to harvest in six weeks. Plants are germinated in trays of rook-whool then transplanted into an Aquaponic system. Students have to check water quality in every system, monitoring pH and elctric conductivity. This way students can learn first handed how to build a sustainable future and get to know the importance of fresh, healthy food.[1] (Green home NYC)

The greenhouse will boast a Vine Crop System vertically-hung which utilizes space in an urban landscape and the Aquaponics system that will eliminate the need for chemical fertilizers by converting waste into nutrients. The Aquaponic system is at the centre of the growing space, breeding up to one hundred tilapias. The rain that is used for fish and plants productions is all collected from rainwater.

A vermicompost system will make use of daily food scraps and will create rich soil to aid the growth of plants in the raised soil beds.

Finally, an Integrated Pest Management system will allow students to monitor pest populations and learn about the relationships of predators and prey in nature.

RG02 - UrbanFarmers, Sasha Glasl - Den Haag (NL)

INTRODUCTION

The roof and the 6th floor of De Schilde, a former Philips factory in The Hague, was renovated to accommodate Europe's largest aquaponics rooftop farm. Urban Farmers AG, based in Basel, Switzerland.

De Schilde, a brick-and-glass flanked seven-storey building, was built as a television and telephone factory for Philips in the 1950s by the modernist architect Dirk Roosenburg. It has about 12,400 sq m of total floor space, largely abandoned but too solid and expensive to knock down. **In the Netherlands, 18% of offices are empty, due to the two last economic crises and cuts in the size of government. Dr Hilde Remøy of Delft University of Technology has predicted office vacancy in the Netherlands will soon reach 25%, the highest in Europe**.

The construction consists of a 1200 sq.m of greenhouse on the rooftop and a 900 sq.m of space for fish cultivation on the floor below. Together, they **should have formed** a perfect symbiotic system for fish and vegetable production within the city. Both floors also house irrigation systems, technical installations and the fish and vegetable processing rooms. A visitors' area with a rooftop terrace allows visitors to experience this spectacular building and its stunning views of the city.

The typical shape of the greenhouse roofline has been retained because it is part of the strong UrbanFarmers identity and emphasises the new use of de Schilde as an urban farming hotspot. By leaving a distinct gap between the existing building and the new addition both entities can be read separately but also as a new tectonic unity.

In July 2018 the project went bankrupt, after which the curator tried to continue the vegetable cultivation and the fish breeding. The activities of Urban Farmers were losing them money from the start, as costs were high and revenue too low.

DETAILS

Client: Municipality of Den Haag

Ending construction: May 2016

Bankrupt the: 2018, July the 4th

Design: Sasha Glasl

Project area surface: 1200 m^2 rooftp + 900 m^2 fish production on the level below

Costs (euro): 2.5 millions

ENHANCE CIRCULARITY

Key Benefits

- Provide fresh fish & vegetable production to tenants and nearby foodservice and grocery retailers
- Eliminate costly maintenance cost of the roof such as water leakage, insulation or roof amenities
- Save energy through better roof insulation with a high-tech greenhouse
- Spread fixed service cost across more tenants

Aquaponics is an innovative, circular method to grow fish (aquaculture) and vegetables (hydroponics) in a closed-looped water system with very high yield, low resource intensity (particularly regarding water and fertilizer) and high-quality, zero-residue products.

FOOD/PLANTS INTEGRATION

Various vegetables are grown, from tomatoes to cucumbers and from peppers to kale even the trandy "microgreens" are sprouting in the sprawling 1,200 sq m rooftop greenhouse. The floor underneath the greenhouse is rented from the municipality of The Hague to farm fish, whose waste products are subsequently used as nutrients for the plants

The eventual hope is to serve 900 local families, plus restaurants and a cooking school, with 500 tilapia a week and 50 tonnes of rooftop veg a year. They've just harvested their first cucumber.[2] (The guardian: Greenhouse in the sky: inside Europe's biggest urban farm")

They are antibiotic/residue free and ultra-fresh local products. Delivered into retail stores and restaurants directly following processing, the products are consistently sold-out in the same business day.

THE BANKRUPTCY[3] ("Vertical farming is difficult in the Netherlands")

When being built it was the largest rooftop farm in Europe; the 4th of July 2018 the Dutch rooftop farm UF002 De Schilde has been declared bankrupt. Back then, in 2013 when the project was approved, the plan was met with great skepticism: thow to compete at all with the gigantic greenhouses in Westland, only a couple of kilometres nearby?

"The current bankruptcy follows a longer process. **The choice of crop could mean a difference.** Growing trout or pike-perch instead of the relatively cheap tilapia, and growing strawberries or blueberries instead of tomatoes and cucumber that are being grown around the corner. Even though it might still be challenging, you're offering a different experience and a product that can be marketed as a specialty." (Reinier Donkersloot with Consult2Grow)

This can be demonstrated considering that only 60 kilometers away, the Amsterdam vertical farm GrowX is expanding. "**I can imagine the difficulty it must be to grow tomatoes and fruiting crops in an urban farm next to a global leader in tomato production, known as Westland**. It is hard to compete in westland prices and price matters", says John Apesos of GrowX.

Following John Apesos ".. while Urban Farmers in The Hague grew all kinds of vegetables & fruiting crops, **indoor vertical farming usually focuses on producing high value leafy greens inside of warehouses near city centers.**"

"The bankruptcy trustee has searched for options for the activities of continue bankrupt. For this, the market has been extensively explored and are approached various interested parties. However, no party appeared to be prepared be in favor of a relaunch at the current location of UrbanFarmers."

RG03 - GothamGreens - Brooklyn (NY)

INTRODUCTION

The company has built and operates over 15 500 square meter of technologically advanced, urban rooftop greenhouses across 4 facilities in New York City and Chicago. Gotham Greens was founded in 2009 in Brooklyn, New York and is privately held.

The Farms

Green Point, Brooklyn NYC
Built in 2011, was the first GothamGreens greenhouse. It was also the first ever commercial scale greenhouse facility of its kind built in the United States. The rooftop greenhouse, designed, built, owned and operated by Gotham Greens, measures around 1400 square meter and annually produces over 45 000 pounds of fresh leafy greens.

Gowanus, Brooklyn NYC
Gotham Greens' second greenhouse facility was built in 2013 in the Brooklyn neighborhood of Gowanus, on the roof of Whole Foods Market's first ever Brooklyn store. The rooftop greenhouse, designed, built, owned and operated by Gotham Greens, measures over 1900 square meters and grows over 90 000 kg of fresh leafy greens, herbs and tomatoes each year. In 1636, Gowanus Bay was the site of the first settlement by Dutch farmers in what is now Brooklyn.

Hollis, Queesn NYC
Gotham Greens' third and largest New York City greenhouse facility is located in the Greater Jamaica neighborhood of Hollis, Queens. Spanning 5500 square meters, the greenhouse, designed, built and operated by Gotham Greens, was completed in 2015 and grows over 5 million heads of fresh leafy greens each year for the New York City market. The climate controlled greenhouse employs advanced automated greenhouse technologies while demonstrating that urban agriculture can be more than a small scale gardening project but rather a robust food manufacturing business.

Pullman, Chicago
Opened in 2015, GothasmGreens largest and most technologically advanced greenhouse built until date, is located in the Pullman neighborhood of Chicago's south side. **Measuring over 7000 square meters, the greenhouse represents the world's largest and most productive rooftop farm**. Our Pullman facility annually grows up to 10 million heads of leafy greens and herbs, year-round, for the finest retailers and restaurants across the greater Chicagoland area.
Spanning nearly two acres, the climate controlled greenhouse facility, owned and operated by Gotham Greens, is located on the second floor rooftop of Method Products manufacturing plant.

DETAILS

Client: GothamGreens

Foundation: 2009

Design: Multiple

Projects total surface: 15,500 m2 distributed on 4 projects

Locations: Brooklyin & Queens, NYC + Chicago

ENHANCE CIRCULARITY

GothamGreens re-circulating hydroponic methods save land and water, eliminating agricultural runoff and chemical pesticides. The greenhouses are all powered by renewable energy and the proximity to the market reduces impacts from transportation.

Hydroponics
Hydroponics is a method of growing plants using mineral nutrient solutions. Nutrients are delivered to the plant in irrigation water eliminating soil. **Water is re-circulated and none is wasted.** The sterile, soil-free growing environment eliminates the risk of pathogens that is particularly important in light of the increase in food borne illnesses, such as E coli and salmonella, from fresh vegetables.

Land
15,500 square feet of greenhouses produce yields equivalent to over 40 ha of conventional field farming. Gotham Greens' methods yields 20-30 times more product per hectare than field production while eliminating any use of arable land.

Water
Agriculture is the largest consumer of fresh water on the planet. Gotham Greens' advanced irrigation system uses 10 times less water than conventional agriculture while eliminating all agricultural runoff. Runoff is one of the leading causes of global water pollution.

Energy
GG's greenhouses rely on natural sunlight for growing operations, not artificial lighting. They are 100% powered by renewable electricity. Efficient production techniques are capable of producing over 50% more crop than conventional greenhouses while using 25% less energy per pound of crop produced. Facilities incorporate advanced thermal design features that substantially reduce heating demand and fossil fuel use.

Food Miles
Gotham Greens' proximity to its customers eliminates the need for long-distance, refrigerated food transportation. Fuel consumption and the associated carbon emissions and air pollution is then dramatically reduced.

FOOD/PLANTS INTEGRATION

Freshness & Health
Produce is harvested just a few hours before reaching restaurants or supermarkets, ensuring absolute freshness and nutrition. Proximity to customers ensures that the extended shelf life is passed onto the customer and not the food delivery chain.

Food safety
Gotham Greens' stringent food safety plans have been developed according to Hazard Analysis Critical Control Points (HACCP) and Good Agricultural Practices (GAP) guidelines eliminating potential for product contamination. The sterile greenhouses minimize the risk of food-borne diseases such as E. coli and Salmonella.

Non-GMO
Gotham Greens' products are verified by the Non-GMO Project, a non-profit organization committed to preserving and building sources of non-GMO products, educating consumers, and providing verified non-GMO choices.

Pesticides free
GothamGreens implements a comprehensive integrated pest management program. This program employs a multi-faceted approach including stringent preventative and monitoring techniques and biological controls. **Beneficial insects are the primary method of prevention and control of harmful greenhouse pests.** A number of beneficial insect species are released and conserved to target specific crop pests for both preventative measures and specific pest targeting. The hydroponic methods completely eliminate the need for herbicides. Gotham Greens employs a reliable, independent, laboratory-verified testing program to ensure its products are pesticide-free. Facilities are cleaned and sanitized daily. All greenhouse team members are trained in integrated pest management practices and educated on identifying pests and pest damage.

INTRODUCTION[1] (The ICTA-ICP Rooftop Greenhouse Lab(RTG-Lab): closing metabolic flows (energy, water, CO2) through integrated Rooftop Greenhouses)

The Rooftop Greenhouse Lab (RTG-Lab) is a research-oriented RTG placed on the rooftop of the ICTA-ICP building in the Universitat Autònoma de Barcelona (UAB) campus (Bellaterra, Spain). The RTG-Lab consists of two i-RTGs of around 125 m2 .

The RTG-Lab is the case study of the "Fertilecity" project funded by the Spanish Ministry of Economy and Competitiveness. The RTGLab aims to demonstrate the feasibility of producing food in RTGs in Mediterranean areas and to analyse and quantify the opportunities of i-RTGs that exchange flows.

The greenhouse of the RTG-Lab is similar to a Mediterranean unheated greenhouse. The structure is made of steel, polycarbonate, LDPE and concrete. The culture system of the RTG-Lab is a soilless crop where perlite is used as substrate. The irrigation is automatic and provides the fertilizers requirements (NPK). The experimental crops (lettuce, tomato) will start on Fall 2014. The RTG-Lab will integrate the energy, water and CO2 flows with the building. As a result, the RTG will utilise, as a first step, residual heat from the building (e.g., lab air), the higher CO2 concentration in this residual air (i.e., which will be used as natural fertiliser), and rainwater collected from the rooftop.

i-RTGs are expected to perform a symbiosis with the building by providing and receiving flows in a bidirectional relation. Nevertheless, the RTG-Lab only integrates, for the moment, the flows in a monodirectional way due to legal constraints. The current Spanish building law, the Building Technical Code (BOE 2006) requires that all the incoming air to a building must be outdoor air. As a result, the greenhouse cannot introduce its residual air to the building.

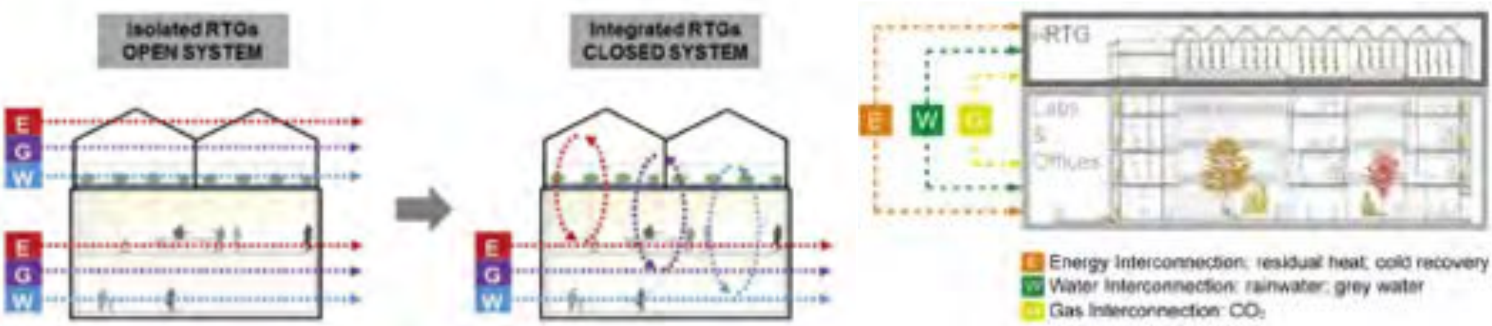
DETAILS

Client: UAB Bellaterra

Construction: 2014

Design: H Arquitectes + DATAAE

Projects total surface: 250 m2



ENHANCE CIRCULARITY

Energy Flow

i-RTGs aim to take advantage from the thermal difference between the building air and the greenhouse air to improve the thermal conditions of the spaces. The RTGLab will use the residual air of the offices and laboratories as a source of thermal difference to regulate the greenhouse temperature. The building air can be used for both heating and cooling the i-RTG. In the Mediterranean context, greenhouses should not exceed 30ºC or be inferior to 15ºC to reach the expected crop yield. During the day and in particular in summer, the RTG-Lab will introduce air from the offices and laboratories with a lower temperature to support the cooling of the greenhouse, when it exceeds 30ºC. On the contrary, the RTG-Lab will introduce warmer air from the building into the greenhouse when its temperature is lower than 15ºC. Temperature of the offices ranges between 18-25ºC degrees. On the other hand, the laboratories are steady-temperature spaces (20ºC). Therefore, both spaces can act as a source of residual air for heating or cooling the greenhouse space.

Water flow

i-RTGs aim to use the water flows from the building as a water source for irrigating the crop. However, irrigation water has to ensure a minimum quality to avoid health risks. In developing countries, wastewater is commonly used a source of irrigation water due to water scarcity. This practice can lead to negative health impacts, such as skin infections (Rutkowski et al. 2007; Raschid-Sally et al. 2009). As a result, the RTG-Lab will only use the rainwater collected on the building roof. The rainwater is stored in a water tank (135 m3) placed in the basement of the building and where a physical treatment is applied. Then, rainwater is supplied to the greenhouse to satisfy the crop water demand. According to climatic data, around 1,5000 m3 could be collected in one year. Contrary to the air flow, the water flow can be bidirectional. The total water demand of the greenhouse for a tomato crop would be of 381 m3. Thus, the crop can be water self-sufficient as the rainwater could satisfy 450% of the demand. The wastewater from the crop can then be redirected to spaces of the building to satisfy the water demand for different purposes.

FOOD/PLANTS INTEGRATION

2(Urban Horticulture: Sustainability for the Future)

The greenhouse system is used to grow tomatoes and beans and verify that rooftop growing can be more economical than growing extensive crops in polytunnels somewhere else outside the city.

It was found that the improved sustainability of growing crops on the iRTG is likely subject of variations depending on the season and the chosen crop.

Crops are grown in **perlite bags (inert base)** and in an open hydroponic system is used for irrigation, supplying the necessary water and nutrients to plants. This system has the advantage of reducing the weight that the building structure has to support in comparison with soil.

Samples are periodically collected from the nutrient solution and the leachates (excess of irrigation in the amount of 30-40%). The concentration of nutrient in these samples

was measured for chloride, nitrite, nitrate, phosphate, sulphate, calcium, potassium and magnesium. Plus, the pH and the EC were measured to obtain an immediate feedback of the total nutrients in solution to adjust it if necessary.

A production protocol has been implemented for the tomatoes, harvesting six representative plants from three different lines. For the bean crops, four samples of 500g each have been collected, determining weight and lenght of each sample pod. All these examples were dried at 60 degrees Celsius and their dy mass was weighted and delivered for the analysis of the nutrients contained. Results show that the cultivation of tomatoes in possible in winter but the yield is lower than expected due to lower solar radiation. Thus, the cultivation of beans was considered as an alternative during winter as it is a less demanding solar crop due to its low height.

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BELLY

INTRODUCTION

The Urban Algae Canopy by ecoLogicStudio [M.Poletto, C.Pasquero] with Carlo Ratti Associati has been presented at the 'feeding the planet' exhibition in Milan with this 1:1 scale prototype.

The show curated by INTERNI in the Universita' Statale is the pinnacle event in the Fuorisalone calendar and featured work from renown architects such as Daniel Libeskind and MVRDV.

The prototype presented by ecoLogicStudio is the world's **1st bio-digital canopy integrating micro-algal cultures and real time digital cultivation protocols within a unique ETFE architectural cladding system**.

Once completed as part of Expo Milano 2015 Future Food District, curated by C.Ratti, the Urban Algae Canopy should have produced the oxygen equivalent of four hectares of woodland and up to 150kg of biomass per day, 60% of which are natural vegetal proteins.

The project is part of the series HORTUS by ecoLogicStudio, special edition for Expo Milano 2015.[1(ecologicstudio.com)]

DETAILS

Client: EXPO 2015

Construction: 2015

Design: ecologicstudio + Carlo Ratti

Projects total surface: 250 m2

Location: Milan

ENHANCE CIRCULARITY

A hybrid of architectural and ecosystem design, the canopy is made to adapt its features based on manual as well as environmental inputs, letting users exert control (via a digital interface) within a larger dynamic system.

"**This process is driven by the biology of mico-algae is inherently responsive and adaptive; visitors will benefit from this natural shading property while being able to influence it in real-time**."

Integrating organic and artificial systems opens up sustainable possibilities for everything from temperature control to power generation methods using advantages of both natural and digital parts.

It is also conceivable that the organic inputs and outputs of such systems could eventually be integrated into the production cycle of urban vertical farms. For now, the canopy will remain a working prototype and proof of concept as well as a chance to experiment with refining the constituent technologies.

Meanwhile, others are taking different approaches to the use of algae in urban objects, including a design for smog-eating algae street lamps and this bio-voltaic table.

With flows of water and energy regulated by weather patterns and visitor usage, this prototype is the **1st bio-digital canopy.** This intersection between technology and biology means that when the sun shines more intensively, the algae would photosynthesise and grow, which in turn reduces the transparency of the canopy and provides more shade. With mico-algae as the foundation of the canopy, it is inherently responsive, which means visitors will be able to influence the building's behavior in real-time.

In addition to CO2 reduction, the canopy as a whole can produce over 300 pounds of biomass daily, all through a relatively passive system that requires far less space and upkeep than conventional civic greenery.

FOOD/PLANTS INTEGRATION

Algae Production
Algae is a single–celled organism known for producing 80% of all oxygen on earth through its highly efficient photosynthetic cycle.
This ability alone makes it one of the most important organisms in the biosphere because, unlike land plants, which must always dedicate a portion of their energy (90%) towards supporting their physical outer structures, such as roots, leaves and stalks, the algae organism, lacking any sort of physical structure, is therefore able to dedicate 100% of its energy into multiplying itself to produce oxygen.

Existing in a range of adapted conditions worldwide, algae can be found in the sea, in freshwater and in wastewater, and range in size from the microscopic, as single–celled organisms which measure only five microns (μ), to the macroscopic, as large seaweeds.
Algae is not only important for its photosynthetic efficiency and ability to produce more oxygen than all plants in the world put together, but its amphibious quality and naturally high lipid content plays a role in its oil producing capabilities.[2]

"The exceptional properties of microalgae organisms are enhanced by their cultivation within a custom designed 3 layers ETFE cladding system. A special CNC welding technology is at the core of it and enables ecoLogicStudio to design and control the morphology of the cushions under stress as well as the fluid dynamic behaviour of the water medium as it travels through it."[3]

As a prototype for an, **"algae–integrated architectural cladding and urban agriculture system,"** the Urban Algae Canopy project demonstrates how algae—when integrated in buildings—can offer important opportunities for creating innovative energy and food production systems within the city; contributing to a sustainable future.

F02 - Green Market, K+C Architects - Abu Dabi

INTRODUCTION

The project
GreenMarket is a food market hall that grows its own food. The concept of the structure is to utilize solar energy as efficiently and completely as possible to grow crops, while providing shade, shelter, lighting, ventilation, and cooling to an enclosed space that is dedicated to other uses.

Hydroponic growing trays can be configured horizontally (as in traditional greenhouses), vertically, or at other orientations, and can be stacked in one or two layers. In our building-integrated approach, the growing assembly forms a double skin enclosure for a space.

Normally, a glass greenhouse is an inappropriate construction type for occupied space for hot climates. In this application, however, the combination of shading and evaporative cooling provided within the greenhouse layer will provide a reasonable thermal envelope for a conditioned space, and a enough daylight will penetrate through the plants to provide abundant natural light within.

This project synthesizes the potential of passive and active technologies - evaporative and absorption cooling, PV, daylighting with active control via moving growing trays, convective and stack ventilation, large openable areas for seasonal cooling - to create a dynamic, exciting, and comfortable environment.[1](the vertically integrated greenhouse - K+C Architects)

The vertical integrated Greenhouse (VIG)
The Facade Farm integrates hydroponic food production into a double skin facade for installation on new high-rise buildings and as a retrofit on existing buildings with adequate solar exposure.

Vertical facades at northern latitudes admit a fairly even distribution of sunlight throughout the year. During the winter, produce prices peak and conventional produce either has to travel great distances or is grown hydroponically in leaky greenhouses with substantial energy requirements. In contrast, a well designed vertical greenhouse integrated with the energy management system of a building, can be energy positive.

The Vertically Integrated Greenhouse (VIG) is a patented system, consisting of plants grown on trays suspended by a simple cable system, and all planting and harvesting occurs at the bottom level. Systems modules can rise as high as 10 or 20 stories each.[1](the vertically integrated greenhouse - K+C Architects)

DETAILS

Client: Aldar

Year of the project: 2010

Design: Kiss + Cathcart Architects / BrightFarm Systems / Ove Arup & Partners

Surface: 8100 m^2

ENHANCE CIRCULARITY

The VIG is structured in modules that are 40 m high. Crops are cultivated in innovative plant cable lift (PCL) systems, composed of two wire cables looped around pulleys, driven by a computerized motor on the farming level. Shallow trays of plants, 2.0 m long, are suspended between the cables by swiveling clamps at each end.

Double skin facade

The double skin façade (DSF) is an innovation which can substantially reduces energy use and increase interior comfort in high rise buildings by providing a second layer of glazingcreating a vertically continuous void space. A DSF provides solar heat gain, buoyancy-driven cooling flows, protection for external solar shades, and sound insulation. Incorporating a VIG into this space both improves the energy performance of the DSF and brings all the benefits of the fresh vegetables.

Adaptative Solar Control System

An adaptive control system alters the angles between rows of plants in the manner of Venetian blind, maximizing solar absorption diurnally and seasonally. Vertical spacing between trays on the cable can also be varied. Rows will be more tightly spaced in winter, when the sun is lower, resulting in steady yields year-round. The vertical alignment of the front and back trays can be controlled by a slight turn of the pulleys, similar to adjusting a Venetian blind. This feature allows the VIG to track solar elevation in real time throughout the day and year, optimizing light capture. Occupants can see out of the building through the 'slats' formed by the dual row of plant trays.

Integrated HVAC system

In winter, the VIG is an effective solar capture device, warming and insulating the glazed facade of the building. On winter nights, exhaust air from the building can be ducted to the VIG to maintain plant temperatures.
In summer, the VIG shades the interior of the building, and provides a source of fresh air to occupants with opening windows. The VIG reduces solar heat gain by absorbing energy as latent heat, through transpiration.

FOOD/PLANTS INTEGRATION

The PCL design is based on a well-established hydroponic method called nutrient film technique (NFT). A thin film of water runs along the bottom of each tray, delivering nutrients to the roots of leafy plants, before flowing down to the next tray. The solution is recovered at the farming level for reuse. Transpiration is limited to 10% of the flow rate by design. Seeds are germinated in flat trays on the bottom level, and planted into the bottom tray. The trays rise up the front of the facade, pass over the pulley, and down the back, returning to the bottom for harvest. The entire trip takes approximately 30 days.

Hydroponic cultivation

Modern hydroponic cultivation produces a superior product with regard to taste, appearance, and freshness. In addition, fruits and vegetables produced in this way are 100% free of chemical pesticides. Recirculating hydroponic food production can yield high quality fruit and vegetables using 10–20 times less land and 5–10 times less water than soil based systems, and is more easily integrated within buildings. As an additional advantage, the soil-less environment in a hydroponic system reduces the chance of pathogenic contamination and substantially improves food security.

Crops

The main crops grown in NFT trays are leafy greens such as spinach, kale, swiss chard, mustard greens, lettuce, arugula, and herbs like basil, parsley, cilantr. These are extremely nutritious and the main fresh vegetables lacking in the average American's diet. The other advantage of these crops is that there is little waste - the whole plant is eaten. Strawberries, edibile flowers and medicinal herbs can also be grown. On the ground level of the greenhouse vine crops such as tomatoes, cucumbers, squash, peppers, which can reach up to 20' high when grown hydroponically, can be grown.

F03 - GreenBelly, AVL Studio - Versatile location

INTRODUCTION

GreenBelly is a vertical garden that can change the future of cities, by making use of the existing walls to produce fresh food in limited spaces. Using recycled materials and organic waste from neighbours, it is a sustainable project that can change the life of urban dwellers!

The vertical garden improves the city from an ecological point of view but also encourages local community participation and social inclusion. It has the potential to help people with limited resources and to provide education in agriculture practices and healthy eating. Local residents become a key part of the system because they help create compost with their daily organic waste.

All large cities have many walls without windows and perfect solar orientation, caused by bad quality urban developments, wasting an opportunity to improve the neighbourhood.
The GreenBelly prototype can be disassembled, stored and moved to different parts of the world, as it can easily fit into a shipping container. Assembling the structure on existing façades is quick and simple, thanks to a modular system.

The module
The modules are presented as "production cabins" designed for the optimised growing of crops at an affordable price. They fit together forming the whole of the garden. They can be disassembled, expanded or reduced, at any time.

DETAILS

Client: No client / Research project

Year of the project: 2018

Design:

Module Surface: 7 (2x 3.5)m^2

Costs (euro): 39 000

ENHANCE CIRCULARITY

The prototype protects the existing façade from external constraints, creating a protective and productive "green belly" for the building. The main advantages for the existing building are the following:

- Balances the temperature inside the existing building.
- Protects the façade from humidity with an extra layer of waterproof material between the garden and the existing wall.
- Reduces sound pollution in the existing façade by up to 10 decibels.

When installing GreenBelly, nothing is wasted. Every available element in an urban context could be used to build the prototype in the most sustainable way. For the structure, we use recycled materials such as scaffolding, construction pallets or concrete form-work wood panels. They are cheap, flexible, easily dismantled materials and they are easy to find in times of crisis when local food is most needed.

The scaffolding structure provides the necessary flexibility to adapt to all types of façades, creating a low-cost modular system. The assembly is fast, clean and simple, with no need for heavy construction machinery.

Depending on the climate, the vertical garden can be thermally open or closed as a greenhouse, through a plastic or glass enclosure, to generate a thermal equilibrium that will benefit the production in the coldest months.

The vertical arrangement optimizes the use of available solar light: solar radiations can reach the different levels through a grid in the ground. It is possible to include photovoltaic solar panels that will provide the electricity needed for the basic functions of the system. The vertical arrangement also favors ventilation by natural convection when the garden is thermally closed. The garden uses rainwater, which moves in a closed circuit falling by gravity from the top floor. Drip irrigation is automated.

FOOD/PLANTS INTEGRATION

GreenBelly uses leftover materials in urban environments, such as scaffolding or wooden pallets. With only 35 m2 of land, a 6-level garden can produce up to 6400 kg of vegetables per year and generates 162 m2 of green area. It can provide organic and affordable salads for residents and people with limited resources.

Production

A single module of 2 m x 3.5 m can produce up to 263 kg of food per year. Growing local varieties and seasonal products will be encouraged, although the most productive varieties in urban contexts with a temperate climate are lettuce and aromatic herbs.

The garden follows permaculture principles, using positive associations of different varieties for good production, without chemicals or pesticides. We will use bees by placing beehives on the upper floor, and other insects as a tool for pest control (not elimination). It is possible to make fresh and local organic salads and sell them on the ground floor or to distribute products to local shops and restaurants.

Production prices are not subject to market changes, due to minimisation of transport, intermediaries and packaging, therefore costs are reduced to a large extent and food products can have fixed prices. This allows selling "zero kilometre" salads without being affected by changes in the prices of origin. People with limited resources, homeless or disadvantaged groups will have priority for the food distribution.

The estimated production of vegetables (20 module-prototype) in a temperate climate is 3,900 kg per year, so by selling the products (at supermarket average price), the price of materials and assembly could be written off in 3 years, which can be reduced if recycled materials are used.


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I01 - GrowX - Amsterdam (NL)

INTRODUCTION

The company grows various types of vegetables in a 'food flat' situated in a corporate building on the Amstel III business park. Amsterdam encourages these urban farming initiatives, with the goal of bringing freshly grown products closer to consumers.

The common goal shared by the Municipality of Amsterdam and GrowX is to be able to offer half the population of Amsterdam vertically grown vegetables by 2025. Through this initiative, this city aims to be a worldwide pioneer. The surface area of GrowX's vertical farm is currently 250 m2.

GrowX currently supplies several top-class chefs and high-end restaurants with its vegetables. "We aim to expand our vertical farm to 2,000 m2, which would enable us to supply half the population of Amsterdam with sustainably grown vegetables, cultivated via vertical farming technology, by 2025", explains Michel Visser of GrowX.

"Vertical farming is carried out in the urban environment, which means less travel time for your tomatoes, for example. Vegetables grown on a vertical farm are cultivated in a high-tech closed system. You can create ideal circumstances here, and as a result harvests are fool-proof. Climate control also renders the use of pesticides obsolete. This means that rinsing and re-rinsing will no longer be necessary. As a result, vertical farming will also save lots of water", continues Visser.

Taking into consideration that the vegetables are grown in layers above one another, space in the city is also used to optimum advantage. The initiators believe this to be a situation that offers only advantages. They call the Netherlands a pioneer in the field of knowledge and innovation in agriculture. Amsterdam aims to become the first city in the world where vertical farming will feed half its population. Start-up GrowX is an initiative launched by American John Apesos and chemical technologist Jens Ruijg.[1](First high-tech vertical farm officially opened in Amsterdam - Hortinex)

DETAILS

Client: GrowX

Year of the project: 2016

Surface: 250m^2

Initial investment (euro): 1.5 millions

ENHANCE CIRCULARITY

GROWx is the first vertical farm in the world to run off renewable energy. Their mission is to actually keep things clean from seed to chef.

Combined with circular packaging, growing and selling locally minimizes our waste and emissions. Plus, it reduces the city's dependence on expensive imports with large carbon footprints.

The farm's smart LED light system ensures every day is a Summer's day without a cloud in the sky.

Working with expert chefs to perfect our climates, we can guarantee rapid growing and predictable nutrient content - meaning the same high quality every single time.

Plants get exactly the right amount of light, air, water and nutrients, and are not sprayed with agrochemicals. "The plants genetics will respond to their environment; with our customers we develop phenotype for that specific seed. When the right seed is in the right production environment, the plant factory will create a consistently wonderful product, every day, year-round" said Apesos.

The modular units have LED lighting and a water tank. "Plants need less water for growing – 90 per cent less than when growing in fields – and less transport is needed because products are grown locally," explained Apesos, who has been developing the seven-square-metre units since 2011.

The water cycle is completely circular and a recycled water systems enable GrowX farmers to use 95% less water than an average field farm.

FOOD/PLANTS INTEGRATION

GrowX aims to grow 180 tonnes of herbs and salad vegetables in the Amsterdam region annually – mainly for the hospitality industry. "Our target customers are responding enthusiastically," says Apesos. "They are drawn to the idea and curious to taste the products" which are:

NO.02
Amaranth Red Army
NO.04
Basil Dark Opal
NO.05
Basil Genovese
NO.06
Basil Thai
NO.10
Broccoli
NO.17
Celery Utah
NO.19
Chives
NO.20
Cilantro
NO.29
Fennel
NO.32
Kohlrabi Purple Vienna
NO.42
Mustard Mizuna Red Streaks
NO.43
Mustard Osaka
NO.44
Mustard Red Giant
NO.45
Mustard Southern Giant
NO.62
Sorrel Large Leaf
NO.73
Borage
NO.92
Mustard Red
NO.93
Nasturtium
NO.94
Radish Rioja
NO.97
Parsley
NO.99
Pea Tendrils

I02 - InFarm - Berlin (DE)

INTRODUCTION

Infarm is an urban farming services company that develops farming tech for grocery stores, restaurants, and local distribution centres.

INFARM is an on-demand farming services to provide urban communities with fresh, nutritious produce, by distributing smart vertical farms throughout the city, directly where people live and eat.

Their autonomous, modular farming units can be stacked to meet any space or demand, whether that be a restaurant, supermarket or even in a warehouse. Each hydroponic farm is monitored and controlled through their robust central farming platform that can adjust the growing environment to ensure each plant gets the best conditions to thrive.

Only 2 years after introducing the concept of in-store farming to the world, Infarm is now operating more than 50 farms across Berlin in supermarket aisles, restaurants kitchens, and distribution warehouses. Infarm is headquartered in the German capital and was founded in 2013.

Today Infarm's team is made up of close to 100 'Infarmers' from disciplines such as horticulture, architecture, industrial design, marketing, and machine learning

Through working on various systems and having to problem-solve for different environments, the company was able to develop a streamlined solution that is easily scalable.
"**Our experience and research has led us to designing the Microfarm - a modular , highly efficient vertical farming building block. With this building block one can build vertical farms in restaurants, hotels, supermarkets, and even at home and achieve the efficiency of state of the art hydroponic greenhouse from the first 1sqm.**"

DETAILS

Client: Supermarkets

Year of the project: 2013

Surface: Not specified

Investment funding (euro): 24 millions

ENHANCE CIRCULARITY

Erez Galonska, Co-Founder and CEO of Infarm, explained: "Rather than asking ourselves how to fix the deficiencies in the current supply chain, we wanted to redesign the entire chain from start to finish; Instead of building large-scale farms outside of the city, optimising on a specific yield, and then distributing the produce, we decided it would be more effective to distribute the farms themselves and farm directly where people live and eat."

Infarm has integrated in-store farming into EDEKA and METRO locations, two of Germany's largest food retailers, where it grows dozens of premium quality herbs and leafy greens, sold at affordable prices. With an output of up to 1,200 plants per month from a single farm unit (2 sqm) Infarm has already enabled some locations to become completely self-sufficient in their herb production.

The distributed farms are connected by Infarm's central farming platform, creating a first of its kind urban farming network. Each farm is a controlled ecosystem with growing recipes that tailor light, temperature, pH, and nutrients to ensure the maximum natural expression of each plant.

Guy Galonska, Co-Founder and CTO, stated: "We collect 50,000 data points throughout a plant's lifetime. Each farm acts as a data pipeline, sending information on plant growth to our platform 24/7 allowing it to learn, adjust, and optimise."

"We bring a world of choice right into your neighbourhood without having to compromise on quality, safety, and taste. Whether that be mint from Peru or an ice-plant from the sandy beaches of Jaffa, by eliminating the distance between farm and fork, we offer produce that has retained all of its nutrients and therefore, intense natural flavour." stated Osnat Michaeli, Co-Founder and CMO.

FOOD/PLANTS INTEGRATION

"This is the beginning of the urban farming (r)evolution: it will redefine what it means to eat well, reshape the landscape of cities, and re-empower the people to take ownership of their food. Our ambition is to reach cities as far as Seattle in the United States or Seoul, South Korea with our urban farming network." said Erez Galonska, CEO.

The Microfarm is INFARM's core innovation. The prototype has gone through various iterations but is now in the final stages of development. The product has gained a lot of interest, and the company received funding through the European Pioneers program that will allow them to mass produce Microfarms and bring them to market.

"The Microfarm is a building block that allows far greater production efficiency than any other product in the market today. From each 1sqm growing tray we harvest 4-6 mature plants every day, 365 days a year. Now, when you stack the trays vertically you increase production dramatically. **The plants grow Hydroponically, on a thin layer of water enriched with fertilisers and oxygen. Custom made LED growing lights mimic different sun spectrums to enhance taste and boost nutritional value**. We use micro sensors and data processing, to ensure that the plants get the best conditions to thrive. Despite of its complexity, the device is easy to use, comfortably controlled by an App, making farming possible for everyone."

Infarm can personalise its farms to each customer's unique needs, growing different varieties for different supermarket locations or equalising the flavour of the produce to better suit the taste palate of a customer's clientele. With a strong group of food retail and leading culinary partners, Infarm plans to grow its farming services beyond Berlin for the first time.

The centre focuses on the promotion of biodiversity and further expanding the company's product assortment; tomatoes, chillies, a variety of mushrooms, fruits, and flowering vegetables are to be introduced next.

I03 - LOKAL pop-up IKEA by Space10 Lab - London (UK)

INTRODUCTION

IKEA's innovation lab Space10 presented a pop-up farm during 2017 London Design Festival, growing tiny greens that were used to prepare 2,000 nutritional salads.

The prototype of this vertical mini-farm is built as a hydroponic system. Rather than soil, crops grow in water filled with just the right amount of mineral nutrients. Using stackable trays and a climate-controlled box, Lokal grows vegetables under modified LED lights that allow year-round indoor growing at a rate three times faster than traditional methods. While the speed alone is impressive, Space10 also estimates this method uses 90 percent less water. The method also creates less waste and eliminates the need for soil or sunlight as part of the growing process.

Space10 worked with interior design studio Spacon & X to create the space. It showcased Lokal, a project that aims to provide a space-saving and sustainable way for people to grow their own food.

IKEA launched the Space10 innovation lab in late 2015, to test product prototypes and find ways of boosting consumers' wellbeing. The lab has since worked on several projects involving food, including a look into the future of the meatball.

More recently, the lab created a dome for growing microalgae, as part of an exploration into unusual food sources.

Lokal forms a continuation of this project, looking at microgreens – tiny sprout-like crops with a short shelf life.

DETAILS

Client: IKEA

Year of the project: 2017

Surface: Not specified

Investment funding (euro): Not specified

ENHANCE CIRCULARITY

Space 10 is introducing smart technology to their concept to make growing the plants easy, so the farm and salad bar concept could easily be rolled out to consumers.

Water
"We grow all of our crops without soil, using only water and mineral nutrients."

Led Light
"Modified LED lights allow all-year-round indoor growing."

Nutritious
"Our food is as fresh as it gets, and packed with wonderful proteins, vitamins and minerals."

Smart Sensors
"Our smart sensors measure, control and learn over time how to grow healthier crops faster."

Clean Energy
We aim to significantly reduce our carbon footprint by using only renewable energy.

Space 10 is introducing smart technology to their concept to make growing the plants easy, so the farm and salad bar concept could easily be rolled out to consumers."

The plants are hooked up to Google's voice-controlled Home device, so that farmers can talk to the plants and find out about nutrition levels.

"The systems were quite technical and our problem was that we needed a technician to operate them," said Caspersen. "

"We thought, if we want to scale this, if we want to make systems like this available to more people, how can we make it much more intuitive to actually operate? So we are starting to explore whether we actually just talk to the farm."

A conversation is started by the command: "Hey Google, let me talk to sprout". Sprout then responds: "Hey there, welcome to our hydroponic farm. I'm Sprout, the voice of all the plants growing around you. How are you doing today?"

FOOD/PLANTS INTEGRATION

The farm was on show at Protein Studios in Shoreditch, east London, throughout this year's London Design Festival. It comprised a wooden structure of approximately two square metres, accommodating three levels of trays filled with crops.

These crops were grown hydroponically, meaning they were set into water filled with nutrients, rather than soil, with artificial lights overhead.

A salad bar was set up in front of the farm, so that the food could be served up straight away. Space10's chef-in-residence Simon Perez produced a total of 2,000 salads during the six-day-long London Design Festival.

Microgreens are typically harvested within 14 days of germination and used as "vegetable confetti" to garnish food. But Space10 found that the root, seed and shoot of these tiny plants are packed full of nutrition, enough for them to become a major source of food.

But to be effective, they have to be served up very shortly after being harvested.

"Microgreens have quite a short shelf life, while our whole food production system is geared towards growing at scale and for it to actually withstand the travel," Space10's Simon Caspersen told Dezeen.

"But here, because we share it while we grow, we can actually share microgreens," he said.

"The beautiful part about microgreens is that the sprout actually contains the same amount of nutrients as the full-grown thing, so that means you get full value of the produce."

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3. Interpretation criteria emerged from the recollection of the case studies

Cities are taking opportunities to improve efficiency and environmental impact by embedding circular economy principles in urban infrastructure and services, from mobility to energy to healthcare [47]. Moving from a linear to a circular economy means minimizing waste and pollution by reducing, recycling, and reusing [48]. In an era where the exhaustion of fossil fuels is a foreseeable future and where human activities are damaging our soils and water resource [6], transitioning towards re-using resources in highly polluting urban environments may be a possible solution to slow down climate change. In this context, 'the Circular City is where it is possible to manage waste, commodities, and energy in smarter and more efficient ways' [49].

In this regard, ZFarming projects can help achieve circular goals within cities, boosting buildings and districts' sustainable development and planning [22]. At the same time, farming in constructed urban settlements can be an opportunity to introduce a new production paradigm, shifting from horizontal food practices to vertical multi-layer, soil-less systems. In this case, the new food production paradigm is a key contributor to enhance circular strategies in urban areas, re-using construction materials, limiting water consumption, and implementing resource exchange between buildings and farming spaces.

Whit this in mind, it was possible to analyze how the selected projects intended to enhance circularity in their communities. The circular features were connected in this analysis to the used food production technologies, trying to assess functional combinations that may result in successful urban farming projects. Unfortunately, to date, there are not many built projects, and sometimes designers' and practitioners' assumptions might not be verified with practical experiences. Aware of this limitation, the interpretation of the selected projects strongly relies on the knowledge extrapolated from the bibliographic research.

3.1 Food and plants integration goals and strategies

The first step to interpret the selected case studies was to assess the potential impact of ZFarming projects on three dimensions of sustainable development: social, economic, and environmental. Out of six encountered potential impacts, three referred to the environmental dimension: (i) improve biodiversity, (ii) land saving, and (iii) reduce the food-mile; two were associated with the social dimension: (i) social embedding & urban transformation, (ii) education - raising awareness on the food production topics; and one connected to the economic dimension: economic development & value creation.

1. Social embedding & Urban transformation

Most of the analyzed projects tend to remark the importance of Urban Agriculture as a boost for social integration. It is noticed that this is considered a fundamental goal in transformation projects such as the new rooftop greenhouses, as well as the Bijlmerbajes Kwartier in Amsterdam. The pillar of social embedding is the integration of new groups of people in an already consolidated social environment, creating new job opportunities within the production process, giving a specific education to people in need to learn a job. That's why it has been noted, that this goal is often linked to goals 3), 5) and 6), and together they have brought to the development of new urban business models.

2. Improve biodiversity

We grew to imagine cities as grey entities, as detached realities far away from nature [8]. Cities and nature have been perceived for more than a century as two separated worlds. The emergency of climate change and the documented health risks connected to the urban reality brought architects, planners, and agronomists to start thinking about how to reduce the green/natural gap in our cities. The selected food production projects fit in this new trend, willing to implement urban green infrastructure. Mostly all selected projects aim to improve biodiversity through the building components or, in the case of the urban scale projects, even with the integration of trees and wider green spaces.

Some ideas like the Algae Canopy Facade studied by the EcoLogicStudio tend to promote breathing organisms with innovative perspiring materials and the integration of algae as urban oxygen producers. Wider, expositive buildings, like the Opal Dome in France, want to boost biodiversity with the integration of proper forest within them. This objective has also been seen in the Santa Clara Agrihood, urban gardens and interior forests are planted to maximize new habitats for local organisms, insects, and birds restoring a micro-urban flora that has growingly been disappearing from our cities. On a smaller scale, even temporary urban installations, such as the Biotope in Copenhagen, use transparent material to attract bees and other insects back into the city.

3. Land saving

In soil-based industrial agriculture, soil health is the most important foundation of a healthy farm ecosystem. Nowadays, the common farming techniques employed in industrial crop production, such as synthetic fertilizer application and mono-cropping, can degrade soil over time, causing a cascade of problems necessitating the use of even more man-made inputs, which in turn contribute to climate change [53].

Some of the selected ZFarming projects, like the rooftop greenhouse, and indoor vertical farming like GrowX and SkyGreens, want to limit soil degradation by taking intensive production within cities. It is important to stress that indoor crops are much more productive than traditional soil-based ones: as we see in the Gotham Greens “15,500 square feet of greenhouses produce yields equivalent to over 40 ha of conventional field farming. Gotham Greens’ methods yields 20-30 times more product per hectare than field production while eliminating any use of arable land” [54].

This process, if expanded to city scale, can impede the land grabbing phenomenon and the abandonment of newly-poor soil for new ones. Moreover, as seen in the above-mentioned projects, old buildings and empty flat rooftops can be easily put in use without occupying new plots in the city. This goal is connected to goals 1), 4), and 5).

4. Reduce the food miles

“Food mile” is a unit used to measure the distance that a food product travels from where it is produced to where it is sold or consumed. The idea of food miles was coined in the 1990s by Professor Tim Lang who worked in one of the agricultural alliances in the United Kingdom. A food mile is calculated by taking the distance traveled by each food ingredient and multiplying it by the quantity of the carbon that is produced by the type of transport used [55]. The result of this calculation has the disadvantage of not being able to indicate whether or not the food product is sustainable.

ZFarming projects aim to sell the produce in proximity to its customers, eliminating the need for long-distance, refrigerated food transportation. Fuel consumption and the associated carbon emissions and air pollution are then dramatically reduced. This is especially the case in those projects where the farming system is integrated into places where the food product is then sold, like restaurants - UCHI and The Greenhouse Restaurant - or supermarkets - the case of InFarm.

5. Education - Raising awareness on the urban food production topic

Some of the selected projects share with the food production, educational goals. It's the case for example of the Manhattan School for Children, included in "The Greenhouse Project", which reflects the vision of a group of parents and educators to create environmental science laboratories on the rooftops of NYC's public schools. In this case, students experience science through interactive technologies such as hydroponic vegetable farming, solar panels, a rainwater catchment system, a weather station, worm composting, and a kitchen corner.

The idea of educating children about sustainability and healthy food from an early age has been considered more and more important through the years to build a more conscious future society. Other projects like the UrbanFarmers BOX and the Biotope, use urban voids to create an installation to raise awareness about Urban Agriculture, showing that a different "agritecture" approach in cities is possible.

In the BioTope project, SJHworks said "…this was exactly the question that led to this project: to see how and if a fully enclosed natural microcosm could survive in a city, in those harsh and hostile conditions. As climate change could irreversibly change the world and our ecosystem as we know it, this study seeks to find ways of integrating nature in our lives, even in harsher environments: could it survive inside the homes of people in a global-warming-stricken world?" [56].

6. Economic development & Value creation

After the analysis of the selected projects, it has been clear that high tech food production Urban Agriculture projects require huge investments. Both small, big, and urban scale projects had to face the importance of an economic return to comply with the loans or the initial investment. It has been noticed that in those ZFarming projects where practitioners only produce and sell food there is a much higher failure risk. That's why, most of the projects, try to create a new business model where food or plant production is the core of a more complex multi-functional building.

Considering the urban scale projects, the production of food is integrated into the buildings completing circular flows, creating new lifestyle models increasing the value of the real estate. In the Bajes Kwartier for example, food production has been reduced to just one tower, while the whole neighborhood proposes all sorts of activities and different housing models. This strategy can comply with different demands, making the differentiation of functions and house typologies the core of its business model.

When approaching a smaller scale, it seemed that projects of edible walls and productive facades face much more difficulties in getting funds, as this typology appears to be difficult to manage, not guaranteeing an economic return. On the other hand, intensive indoor farming is flourishing now, with projects like InFarm getting more investments by the government and the banks [57].

3.2 Circular features in the selected case studies

Particular attention in the analysis of the case studies was put in the way ZFarming projects may enhance circular processes on the local scale. This analysis focused both on food production strategies and construction materials and methods. In this regard, the circular economy here has intended as that process where the value of products and materials is maintained for as long as possible. Thus, waste and resource use are minimized, and when a product reaches the end of its life, it is used again to create further value [50]. This could bring major economic and environmental benefits, contributing to innovation, growth, and job creation.

Eight common circular features have been encountered and put into relation with each other. These Circular Features (CFs) are:

1. *CF1: Transformation (in case of retrofitting projects)*

Transformation, instead of demolition and reconstruction, is about physically preserving buildings or building components. The concept is to functionally repurpose them as construction parts of the new buildings. This process has been encountered in the Bajes Kwartier in Amsterdam, where concrete walls, steel doors, and corridors from the old prisons have been included in the Masterplan as new construction materials. On a smaller scale, also The Greenhouse Restaurant used parts of the old barrack for the new building. In this case, the old glass panels determined the height of the greenhouse. Furthermore, as a temporal project, cezeped designed the building already thinking of its future demolition. In this case, it will be possible to dismantle the building and either reconstruct it elsewhere or reuse those materials for other building constructions.

Because of this, there is less need for new building materials. Outputs from old buildings can become inputs for new ones, even determining their design and measurements. This feature is connected to features number 2) and number 6).

2. *CF2: Material Reuse and Recycling*

In addition to transformation, building components can be reused and made visible in new buildings as interior parts: this is how wasted materials can be incorporated in building construction. In The Greenhouse Restaurant, almost all interior furniture was made of recycled materials, as well as floors and even screws. Demolition parts and material can have a second life and be applied to new constructions elsewhere in the city. Also, it is possible to re-use other architectural elements and give them a new life, as in the case of the UFU Box, designed by the Urban Farmers in Switzerland. Here, and the old container has been repurposed and used as an installation technical box to feed and monitor a small greenhouse put on top of it.

Material Reuse and Recycling is different from the Transformation feature in terms of scales and repurposing. In the first case, the elements of the pre-existing building (such as windows, facades, and even structural components) are used to transform it, giving it a new architectural life. In the second case, materials are recycled from other parts of the city and other buildings and used for completely different new functions. Another interesting case was the S*Park project designed by Tres Birds in Denver. Here, almost all the bricks, including the ones used in the facade of the UCHI restaurant were reclaimed. This feature is connected to features numbers 1), 4), 6) and 7).

3. *CF3: Water management & Water conservation*

In building-integrated agriculture, water management and conservation are some of the most important goals to achieve. This is because both buildings and soil-less farming require a huge amount of water to satisfy the needs of their users (people in one case, plants in the other). The integration of buildings and soil-less farming has resulted in a win-win combination in most of the selected projects, as the water from the buildings and collected rainwater could be re-used in the soil-less farming system. Rooftop greenhouses projects seemed to be particularly efficient in this sense. For example, the iRTG of the ICTA building in Barcelona successfully managed to use collected rainwater as a water source for irrigating the crops. Here, rainwater is stored in a 135 cubic meter tank in the basement, and treated before watering the crops. As the amount of collected rainwater is four times the greenhouse demand, it can be then redirected to the office spaces and used for different purposes.

Furthermore, in closed hydroponic systems water can be reused multiple times. This is the case of the Gotham Greens project where its CEO said that they use ten times less water than traditional agricultural, reducing to a minimum their farming runoffs. A different example was found in the Administrative building in Oberhausen, where greywater from the building is processed in the cellar and re-used in the offices. The extra water is pumped into the integrated greenhouse and used as irrigation in the development and research area. Another interesting concept was studied in the Copenhagen Biotope, where the polycarbonate shell collects rainwater and leads it into the soil through small holes in the envelope. As the installation is temporary and nobody can access the inside, the idea was to build a self-watering greenhouse where plants could grow on soil. It is linked to features 5) and 8)

4. *CF4: Waste recycling*

Industrialized urban areas are immense waste hubs, as most outputs produced by citizens are difficult to reuse. When investigating how to recycle waste in the ZFarming project there are two aspects to keep in mind. The first one regards waste produce by human activities, which can be redirected into the farming spaces. The second one concerns wastes produced by the farming activities, the runoff of the production, which must be minimized. Human organic waste is identified in some projects, like the Regen Village concept, as a powerful source of energy that can be used as alternative biogas.

A similar concept has been used in SPARK's HomeFarm proposal, where agricultural waste, consisting of plant cuttings and other materials used for maintaining the farm, was used to feed a biogas power plant. The ashes produced by the power plant were then supposed to act as fertilizer for the traditional gardening area. In the Bajes Kwartier project, organic waste could also be sold as a natural fertilizer to the local community creating a micro-economy itself. This feature is connected to features 2), 5), and 6).

5. *CF5: Use of renewable energies & energy flows*

The use of renewable energy is reported in almost every project that has been studied. This is probably connected to the fact that indoor farming and soil-less greenhouses require huge amounts of energy to operate. Solar and photovoltaic panels are the most used technologies to partially power buildings and farming areas. It is possible to see them in The Greenhouse Restaurant, in the UCHI, and most rooftop greenhouses. Projects at the urban scale reported more complex energy systems except for the Santa Clara Agrihood, to date the only one that has been built. In the Home Farm in Singapore, a biogas power plant integrates solar energy production. Both in ReGen village and Bajes Kwartier concepts, a power grid is connected to the solar energy sources and gives energy to the houses. In the ReGen village, a biogas power plant fed by organic wastes is connected to the smart grid. Here, the concept is to take energy from the grid and give it back if not needed, to maximize efficiency. In the Bajes Kwartier, the power grid is connected to geothermal plants. In the Groene Tower, a Power Nest generates energy from the wind and integrates the energy produced in the cellar area by a waste transformer.

The analysis of the projects confirms that renewable energies can be used to produce a project's energy and partially power the farming spaces. Solar cells, photovoltaic panels, heat pumps, geothermic pumps, and bio-gases can be linked to a smart grid, which will provide energy for the homes, buildings, and clusters allowing the inhabitants to feed stored electricity back onto the grid when not needed. In most concepts, this surplus of energy in the smart grid can be used to charge electric vehicles. Of course, some of the selected projects are not yet being completed (like the Bajes Kwartier and the Groene Tower) or will probably never be built (like HomeFarm and the ReGen Village). This causes a lack in the practice of most of the energetic concepts they proudly carry on. In this sense, solar energy together with smart energy strategies seem to be most effective and practicable.

Smart energy strategies include the exchange of heating and cooling between architectural and farming spaces. In Oberhausen for example, the waste heat is led from the job center directly into the R & D area. In the UCHI restaurant, solar gain is contained in the greenhouse where the large concrete slab acting as thermal mass, regulating temperatures above and below. Another state-of-the-art functional example is represented by the ICTA building, where the RTGLab uses the residual air of the offices and laboratories as a source of thermal difference to regulate the greenhouse temperature. The building air can then be used for both heatings and cooling the i-RTG. This feature is linked to features 3), 4), 7) and 8).

6. *CF6: Transportation management*

In a global food system, a great part of the food that we encounter on supermarket shelves in industrialized cities is coming from other regions of the world. ZFarming projects aim to dramatically reduce the distance between spaces of consumption and production areas. In most urban scale projects, this is also connected to strategies aimed to reduce vehicle trips, excessive parking, and greenhouse gases, while making transportation more affordable. For example, in the S*Parks projects, the planners designed a big parking garage just underneath the neighborhood, making it only accessible by foot and electric vehicles.

Commercial projects such as the Gotham Greens spread in various US cities, aims to sell locally, reducing environmental costs connected to refrigerated transformation. The same concept has been developed by InFarm, where food is produced, stored, and sold right in German supermarkets, guaranteeing always fresh products, limiting the transportation to the only production boxes. In this case, food can be produced, stored, and consumed in place. This feature is linked to features 1) and 2).

7. *CF7: Material choice & Passive solutions*

Material choices and passive solution strategies were used in most built projects to reduce energy consumption, maximizing the efficiency of the farming spaces. Proposed construction materials (both reused and new) can improve energy conservation within the projects as well as reduce carbon emissions emitted by the material itself or during its fabrication. This was an important element of the Bajes Kwartier, which obtained materials patent for its buildings, participating in the BAMB Project (Building as Material Bank). The BAMB project started in September 2015 and "[…] will enable a systemic shift where dynamically and flexibly designed buildings can be incorporated into a circular economy. Through design and circular value chains, materials in buildings sustain their value […] slowing down the usage of resources to a rate that meets the capacity of the planet" [51]. Thus, in the case of the Bajes Kwartier, buildings themselves become a materials bank for the future project, pushing towards more sustainable constructions.

Together with the use of smart materials, implementing passive solutions can be a powerful tool to reduce energy loss. In the UCHI greenhouse for example sensors around the greenhouse allow to turn on fans or heaters, open up roof and side vents to adjust the humidity and temperatures depending on the internal and external climatic conditions. In this way, it is possible to make the greenhouse the perfect environment for growing leafy greens. External climatic conditions can in-fact affect fruits and vegetable production. In the Brooklyn Gotham Greens project, for example, the completely translucent rooftop greenhouse relies exclusively on solar light, not needing any artificial lightening. Another aspect for implementing passive solutions design is to use the farming spaces to improve buildings' climatic control. In the Green Belly conceptual project, adding a facade to an existing blank wall is thought to (i) balance the temperature inside the existing building: (ii) protect the façade from humidity with an extra layer of waterproof material between the garden and the existing wall; and (iii) reduce sound pollution in the existing façade by up to 10 decibels. In the UCHI restaurant instead, the rooftop greenhouse works as thermal storage and reuses it to the downstairs restaurant. This feature is connected to features 1), 2), 5) and 6).

4. Conclusions

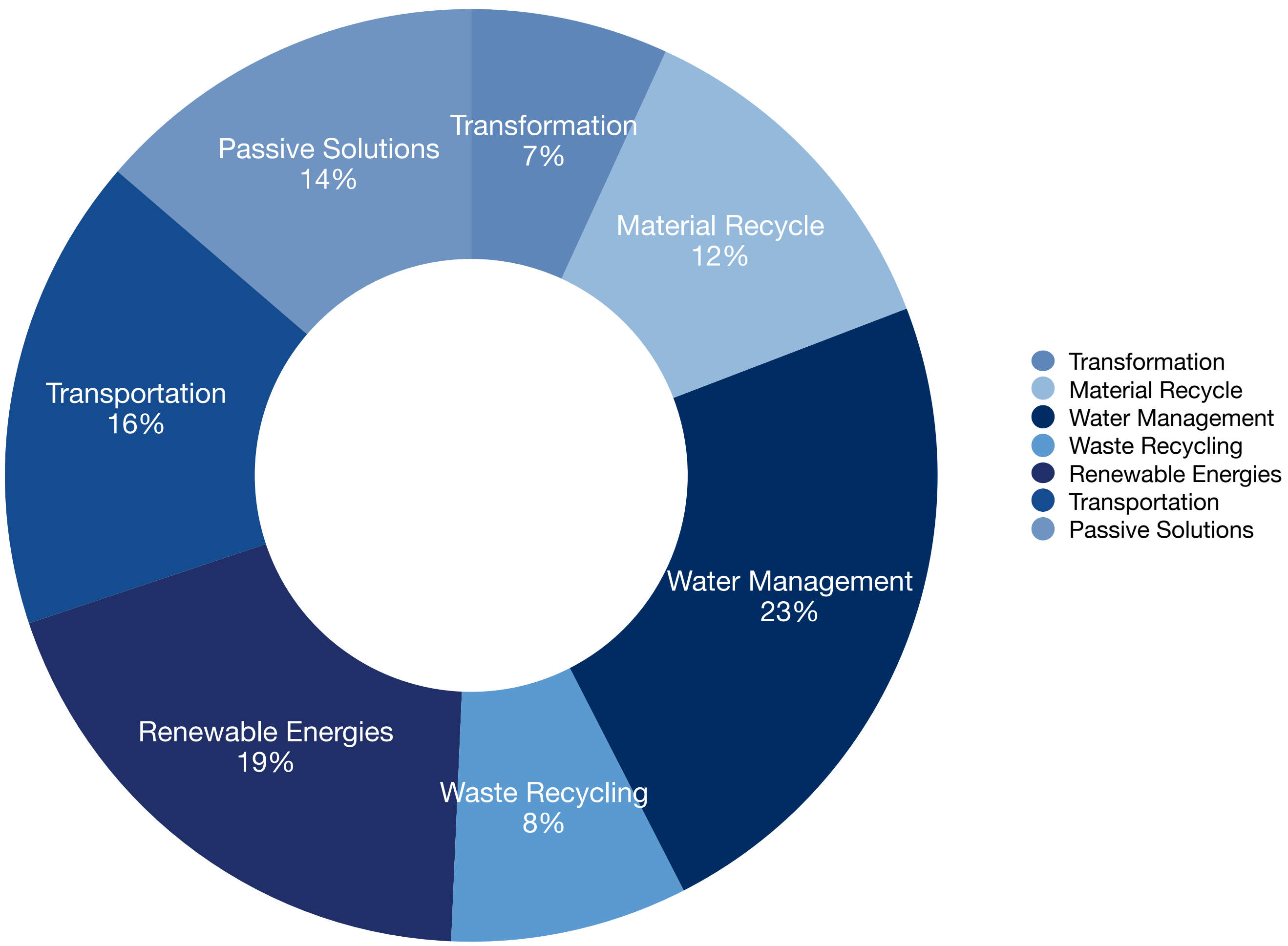
During the analysis of the case studies, it was noticed that each selected project shared one or more of these features with the others, characterizing different approaches towards circularity depending on the scale of application (Table 1). In ZFarming projects, circularity goals apply to two entities: (i) the buildings, and (ii) the farming systems. Thus, the great potential of these initiatives consists of creating osmotic relationships between these two entities. In this regard, the connection between architecture and food production systems could provide new environmental benefits for the selected project. In this sense, Table 1 connects each circular feature to each of the selected case studies to evaluate the total usage of each feature.

Tab. 1: Circular features associated with to each case studies

CODE	CF. 1	CF. 2	CF. 3	CF. 4	CF. 5	CF. 6	CF. 7
U01	X	X	X	X	X		X
U02		X	X	X	X		
U03		X	X	X	X		
U04			X		X	X	
UI01		X	X		X		
UI02			X			X	
B01			X		X		X
B02		X					X
B03		X	X	X	X	X	X
B04		X			X	X	X
B05		X			X	X	X
RG01			X		X		
RG02	X		X		X	X	
RG03	X		X	X		X	
RG04			X		X		X
F01			X				X
F02			X			X	X
F03	X	X		X		X	X
I01			X		X	X	
I02			X			X	
I03	X		X		X	X	

When analyzing the selected projects, it was noticed that there is a huge gap between built projects and conceptual proposals. For the latter, it is difficult to assess whether the circular food production goals will be met if they were to be built. In this regard, more answers may come from the Bajes Kwartier, which is now in construction, but it will still need some time after completion to assess its success. On the other hand, the concept designed for the ReGen Village in Almere looks promising, but there is still no financial support to build it, and planners from Oosterworld declared that they haven't heard from them in years [52]. Building on a smaller scale seems more doable at the moment; projects like the ICTA building in Barcelona, the UCHI in Denver, the office building in Oberhausen, and The Greenhouse Restaurant in Utrecht are successful examples of building-integrated agriculture. What emerged from these experiences is that, for successful integration of food production within architectural buildings, mixing functions and different purposes is crucial. Research, commercial and educational purposes are mixed and work as powerful incentives to attract different investments. Purely commercial rooftop greenhouses may struggle to succeed. The Gotham Greens Project is thriving in a complicated US market and expanding its greenhouses throughout the American territory. On the other hand, the Urban Farmers' experience in The Hague failed in a couple of years, as their products struggle to find a place in a saturated market where produce from the neighbor Westland greenhouses had more competitive prices. Furthermore, a limitation of the studied commercial rooftop greenhouses is that there is no relationship whatsoever with the buildings they are standing on. In this regard, it seems that new building construction would allow better integration between the food production system and the building itself.

Fig. 3: Application percentage of circular features in the selected case-studies



Extrapolating the results from Table 1, and reporting them in the chart illustrated in Fig.3, it is possible to see that Water Management and the use of Renewable Energies were the more used features to boost circularity and sustainability in the selected projects respectively used in 17 and 14 projects. Most of the time these two features were accompanied by the use of recycled materials and passive envelope solutions. Another feature that was encountered in most projects was related to transportation management, with 12 projects that clearly stated that they intended to dramatically reduce food transport by selling within the same area of production. Less common features were Transformation and Waste Recycle. Regarding transformation, that is probably because ZFarming projects built on existing buildings were commercial rooftop greenhouses that mostly didn't interact with the pre-existent structure. Concerning waste recycling, most of the projects that proposed to reuse human and production waste were theoretical ones. This may be due to the fact that the current legislation limits the use of waste for food production, as it might contain harmful pathogens that could endanger people's health [58]. Furthermore, depuration of converting plants might be expensive and hard to operate, especially on a smaller scale than the urban scale.

In conclusion, the analysis of the selected case-studies provided interesting insight regarding the possibilities and the benefits coming from the integration of food production systems within the built environment. However, it was possible to appreciate a clear difference between realized and not realized projects. A notable issue is represented by the scale of the project: indeed, most of the realized projects were at a smaller scale compared to theoretical projects. Inspirational designs like the Home Farm in Singapore and the Re-gen village in Almere are destined to remain on paper, and they will never see the light. Possibly, the investment to sustain such projects is still too high to make them effectively being taken into consideration by municipalities and developers. In the next chapters, this research will investigate more the possibilities that advanced hydroponic systems may provide. In particular, this thesis will go deeper into the analysis of water and waste management in Building-integrated agriculture projects.

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PART 2: Design inputs for the integration of advanced Urban Farming projects in architecture

- Chapter 3: Advanced hydroponic technologies
- Chapter 4: Beyond food production: closing water and nutrients loop in green buildings through an integrated hydroponic wastewater treatment plant

Chapter 3_ Advanced hydroponic technologies

Preface

Finding new spaces for agriculture in urban environments drove scientists and researchers to develop new technologies that can maximize yields in limited spaces. Thus, removing the constraints of the soil using other media to grow plants in buildings has seen increasing attention and research in the past ten years [1]. In this scenario, ZFarming experiences rose as a subtype of already existing urban farming concepts taking advantage of vertical spaces in cities to increase urban food production. The advantages of ZFarming projects and the integration of agricultural systems within buildings are not only connected to the possibility of producing food without occupying urban grounds, but also in the way they could implement synergies between buildings and agriculture [2]. In this regard, the application of advanced farming systems within the constructed environment represents a new opportunity for planners, architects and engineers to use integrated UF projects to implement circular flows of resources in cities.

Cities are in-fact the hubs where circular strategies can be experimented and implemented: here, the confluence of government actors, business and citizens "[…] creates live innovation labs for addressing the complex challenges of linear economic models" [3]. Furthermore, local municipalities can act faster than national governments, making it more agile for cities to transition towards circular policies [4]. Transitioning to a circular economy requires rethinking market strategies and models that encourage the responsible consumption of natural resources, educating consumers, proposing new sustainable behaviors [3]. Once implemented in city, the circular economy could [3]:

(i) create a circular supply chain, in which residual outputs from one process feed into another process;
(ii) recover the resource value of materials in a manner that creates new value from these same materials;
(iii) extend the work-life of a product and encouraging access and retaining ownership;
(iv) improve the usage rates of products through shared use.

In this context, as emerged from the bibliographic research and from the analysis of 21 selected cases studies, implementing building-integrated agriculture is coherent with cities' circular development goals. To this regard, closed-loop agricultural ecosystems can treat waste as a resource. In metabolic synergies between buildings and farming, the waste of one part of the system can become the nutrients for the other. Thus, a closed-loop system recycles and reuses nearly every element of the farming process, from dirty water to nutrients [5]. Furthermore, food waste can also be converted into organic matter and used either as compost for other agricultural practices or as burning bio-fuel in bio-gas plants. Ideally, in closed-loop systems, everything remains in the system, leading to a zero-waste outcome [5].

In this chapter we will proceed with the analysis of advanced off-soil food technologies extrapolated from the 21 case studies reported in Chapter 2. The aim of this analysis is to determine advantages and disadvantages in terms of food production, energy and resource efficiency of off-soil technologies. Furthermore, it will be highlighted how the application of advanced ZFarming models can enhance circular economy strategies in Northern European settings. The scenario in which these relationships between food production and circularity is analyzed has been extrapolated from the selected case studies and confronted with local policies. The choice of the Northern European setting depended from three main factors: (i) it was possible to find more accurate documents about the selected projects, with possibility to retrieve data, visit the project sites and communicate directly with local governments and municipalities; (ii) the agro-legislation regarding urban farming projects was considered more developed and defined; and (iii) it has been reported a better cultural knowledge and acceptance towards urban farming projects.

1. Off-soil production technologies and methods

Adopt advanced farming methods in ZFarming projects could provide greater yields in spite or relative small production spaces, using far less water than traditional farming [6]. The development of high-tech farms, from the design to the production configuration, must ensure optimal light exposure, along with the correct dosage of nutrient solution for each plant. It has been reported in literature [1, 6, 7] that controlled, closed-loop environment farms would dramatically reduce the need for harmful herbicides and pesticides, maximizing plants' nutrition values. Constant research is carried on all over the world aiming to develop and adapt high precision off-soil farming methods in order to deploy them everywhere in the planet, minimizing their environmental impact [5]. However, farming methods and technologies should be tailored for the climatic, social and economic context in which each specific ZFarming project wants to be developed. Hence, to proper assess the beneficial effects of a certain project, determining the scenario of intervention is crucial to minimize waste and implement the overall sustainability of the project.

Nonetheless, from the analysis of the 21 case studies it was possible to identify one common technological system that was used mostly in all projects and declined in different ways depending on the environmental and financial circumstances, the type of crop that was cultivated and the available space. This method is commonly known as Hydroponic system and in this macro-category follows several different declinations of soil-less agriculture. Two main systems that derive or are accompanied from the hydroponic methods and that were found in the analysis of the state of the art are: (i) Aeroponics, which is an enclosed air and water/nutrient ecosystem that fosters rapid plant growth with little water and direct sun and without soil or media [8]; and (ii) Aquaponics, which is a bio-system that integrates recirculated aquaculture (fish farming) with hydroponic vegetable, flower, and herb production to create symbiotic relationships between the plants and the fish [5]. Several combinations can be used in these three systems, from high tech solutions to more "home-made" ones. Variations can be determined by the media used to grow food, by the irrigation technique and by the substrate. In this part of the research, we will characterized these systems and analyze the possible variations that can be used in ZFarming projects.

1.1 Characteristics of the Hydroponic systems

Hydroponics is a method of growing plants using mineral nutrient solutions. Nutrients are delivered to the plant in irrigation water eliminating soil. This way, the hydroponic methods dramatically reduce the need for herbicides, avoiding soil-borne diseases that have always been a problem in the traditional soil-based agriculture and in greenhouse cultivation industry [9]: here, the sterile, soil-free growing environment eliminates the risk of pathogens that is particularly important in light of the increase in food borne illnesses, such as E coli and salmonella, from fresh vegetables [10]. Different applications of the hydroponic technology have been encountered in the analysis of the selected case studies. For instance, in the ICTA building crops are grown in perlite bags (inert base) and within an open hydroponic system that supplies the necessary water and nutrients to plants: this system has the advantage of reducing the weight that the building structure has to support in comparison with soil. In the GreenMarket designed by K+C in Abu Dhabi the architects estimated that the hydroponic food production can yield high quality fruit and vegetables using 10–20 times less land and 5–10 times less water than soil based systems using a close system. In literature, reported advantages of the hydroponic cultivation compared to soil grown crops are [8]:

- Pathogen-free start with the use of substrates other than soil and/or easier control of soil-borne pathogens.
- Growth and yield are independent of the soil type/quality of the cultivated area.

- Better control of growth through a targeted supply of nutrient solution.
- The potential for reusing the nutrient solution allowing for maximizing resources.
- Increased quality of produce gained by the better control of other environmental parameters (temperature, relative humidity) and pests.

Open Systems vs Closed Systems

As seen in the two previously reported projects, hydroponic systems can be divided into open systems and closed-loop systems. The substantial difference of these two systems is that in open hydroponics loops the superfluous nutrients are not recirculated, and may either deposit on the ground and water bodies or used as irrigation for soil-based agriculture [9]. Closed-loop hydroponic systems collect and re-use the superfluous exceeding nutrients, re-circulating them back into the system. Open systems are the most commonly used in soil-less agriculture, even though regarding economics and environmental concerns, closed systems are desirable [9]. There are several reported advantages and disadvantages of close hydroponics production, which should be considered when approaching ZFarming projects. The advantages of closed systems are [9]:

- A reduction in the amount of waste material.
- Less pollution of ground and surface water.
- A more efficient use of water and fertilizers.
- Increased production because of better management options.
- Lower costs because of the savings in materials and higher production.

The disadvantages are [9]:

- The required high water quality.
- High initial investments.
- The risk of rapid dispersal of soil-borne pathogens by the recirculating nutrient solution.
- Accumulation of potential phytotoxic metabolites and organic substances in the recirculating nutrient solution.

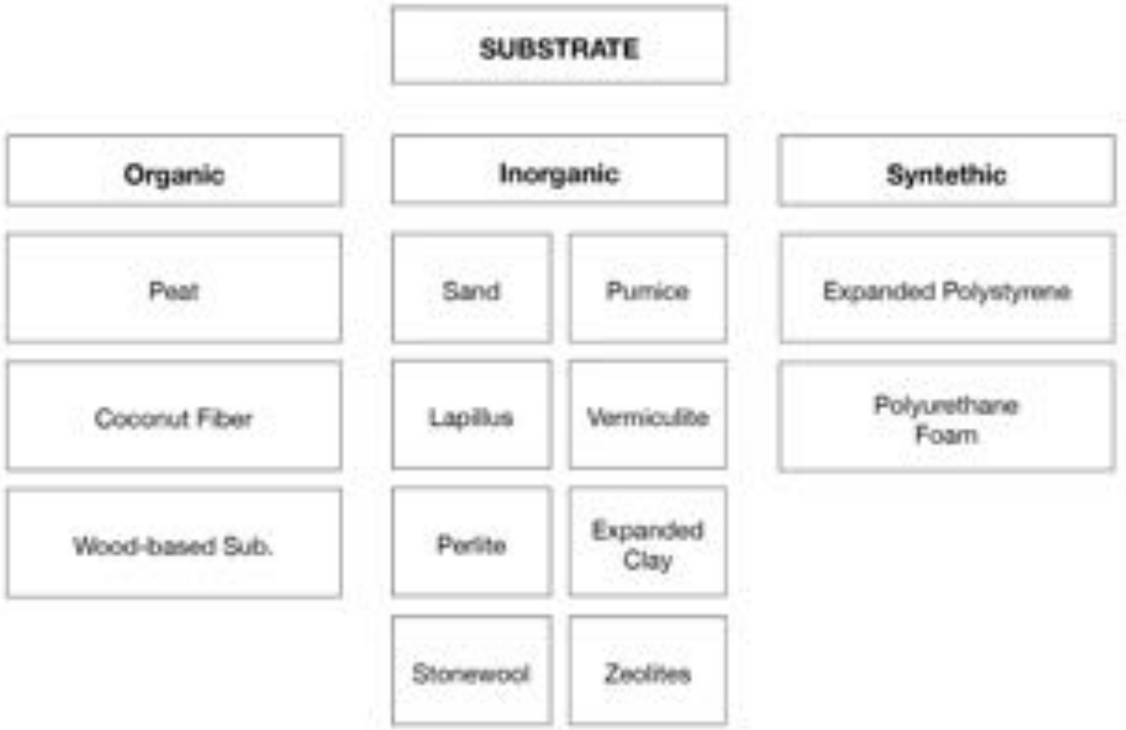
Substrate vs No substrate

Another differentiation of hydroponic systems is the utilization of substrate (aggregate system) or water solution as growing media.

Solid Media Culture (Aggregate system)
In the first case, substrates are necessary for the anchorage of the roots, a support for the plant and also as a water-nutritional mechanism due to its microporosity and cation exchange capacity [9]. The media material selected must be flexible, friable, with water and air holding capacity and can be drained easily [11]. In addition, it must be free of toxic substances, pests, disease causing microorganisms, nematodes [11].

Growing plants in soil-less systems causes unbalances in the shoot-root ratio. Due to this unbalance, plants need far more water, air and nutrients than in ground-based open field cultivations. Using a substrate is then necessary to ensure stable chemical–physical and nutritional conditions [9]. Several materials can be used as substrates (Fig. 1), with different characteristics and costs. Nonetheless, there is not a universal substrate that guarantee optimal growth for every plant cultivated in soil-less system. For this reason, substrates must be carefully chosen based on plants physiology. When choosing the substrate, it is possible to highlight three major material categories [9] (Table 1):

Fig. 1: Different categories of substrates.



Source: Own elaboration based on *Malik, Aatif & Iqbal, Kaiser & Aziem, Showkat & Mahato, Prasanto & Negi, Ajeet. (2014). A Review On The Science Of Growing Crops Without Soil (Soilless Culture) – A Novel Alternative For Growing Crops. International Journal of Agriculture and Crop Sciences.*

1_ Organic Materials: This category refers to natural organic substrates. This may include residues, waste and by-products of organic nature derived from agricultural [9] as well as industrial or urban wastes. For instance, it is possible to use as substrate by-products of the wood industry, or organic wastes from urban settlements such as sewage sludge. Due to their organic nature, these kind of substrates are subjected to fast decomposition processes, which may cause root aeration problems. For this reason, when using organic substrates may be preferred to grow short-cycle crops [9].

2_ Inorganic Materials: This category includes all sort of natural materials, like sand and pumice, as well as mineral materials derived from industrial processes, like vermiculite and perlite [9]. Not being subjected to organic degradation, inorganic materials are preferred to grow medium and long-cycle crops. Due to their resistance and performances, inorganic materials are the most used in commercial hydroponic plants and research facilities.

3_ Synthetic Materials: This category may include both low-density plastic materials and ion-exchange synthetic resins [9]. These materials, called “expanded”, because they are obtained by a process of dilation at high temperatures, are not yet widely used. However, as they possess certain physical properties that allow to balance the characteristics of other substrates, integrating them to improve their porosity and drainage capacity. These type of substrates don’t decompose [12], thus once they are not needed anymore this may be cause of disposal issues.

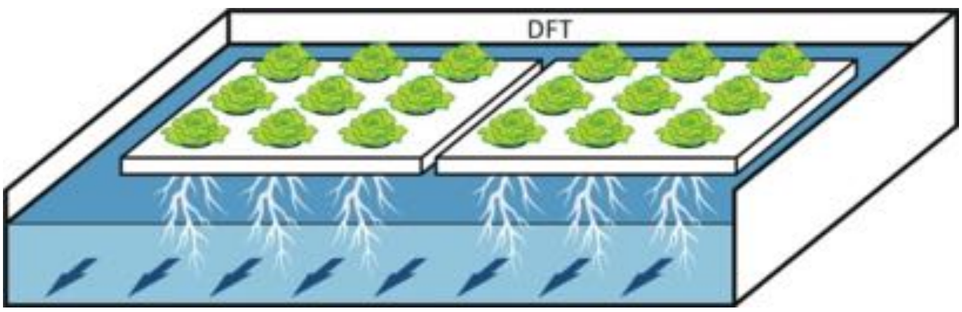
Table 1: Substrate characteristics

	Advantages	Disadvantages	Use
Organic Materials	Natural materials derived from recycling processes. Easy to dispose.	Subjected to organic degradation. Limited use.	Short-cycle crops.
Inorganic Materials	Longer resistance than organic materials. Guarantee better growing performances.	Depending on the chosen material. Tend to deteriorate after time and multiple usage.	Medium, Long-cycle crops.
Synthetic Materials	High porosity and water absorption proprieties. They don't decompose.	Disposal issues due to their synthetic nature.	Integrate existing substrates to improve porosity and drainage capacities.

Solution Culture or Liquid Hydroponics
Opposite to the solid media culture that uses substrates, solution culture or "liquid hydroponic" lets the roots floating in water or air. Three main types of hydroponic systems can be found according to nutrient and water distribution:

1_ DFT: Deep Flow Technique: In this cultivation technique, plants grow on hanging supports such as rafts, boards or panels [9]. The supports are floating over 10-40 centimeters deep containers filled with the nutrient solutions. The containers, or tanks, can be constructed with different materials and waterproofed with polyethylene films [9]. The floating rafts serve as a support for the plants and are typically made of extruded polystyrene foam or low-density polyethylene [13]. Through holes in the rafts, plants' roots penetrate directly in the water tank filled with the nutrient solution. Roots are then always submerged in water, hence there is no need to pump water in the system. Nonetheless, as water is not recirculating it is important to integrated an air compressor to constantly oxygenate the solution. For this reason, it is preferred to grow short-cycle crops, like lettuce, in DFT hydroponics method. The forced aeration process is usually done through the use of air stones or other perforated pipes. The water solution needs to be always kept at cool temperatures, between 18 and 24 °C [14]. This advantage of this system is the possibility to minimize costs and managements, as it doesn't need much maintenance. The rafts materials permit high insulation values and together with the high ratio of solution volume to surface area make DFT systems the most thermally stable hydroponic systems [14].

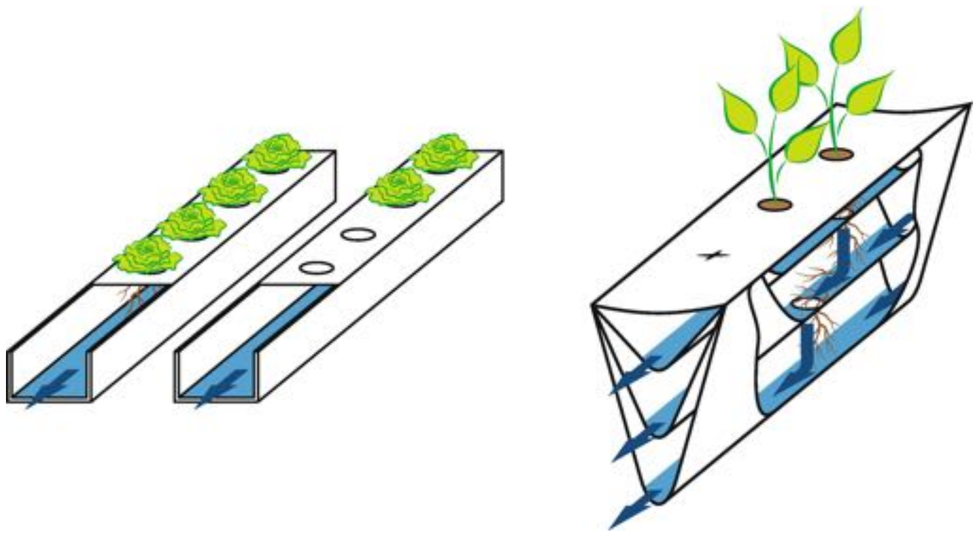
Fig. 2: DFT system with floating panels



Source: *Maucieri et al. (2019) Hydroponic Technologies. In: Goddek S., Joyce A., Kotzen B., Burnell G. (eds) Aquaponics Food Production Systems.*

2_ NFT: Nutrient Film Technique: The nutrient film technique (NFT) was used as hydroponic cultivation already in the second decade of the twentieth century [14] and can now be considered the 'classic' hydroponic system [9] as it has become the most common hydroponic method for the production of salad greens and herbs [15]. Here, the nutrient solution constantly circulate in sloped troughs within 1-2 centimeters layer of water [9]. The fertilizer solution is pumped from the reservoir into the high side of the troughs and then flows down through gravity. At the end of the NFT troughs there is a gutter that transport the water and the exceeding nutrients back into the water tank [16]. The troughs are usually made of food grade PVC (polyvinyl chloride) and can range from less than1.5 m to over 20 m in length and they can either have a circular or rectangular section [14]. Reservoir level, electrical conductivity (E.C.) and pH of the water must be checked daily. To this regard, one of the advantages of the NFT system is the automatization with dosing machine that can guarantee optimal growing conditions [9]. The lack of substrate is an advantage to reduce costs and favor plant growth, nonetheless the low water levels make the system susceptible to pumps failure problems. Clogging issues may also come from the appearance of algae in the nutrient solution when this is exposed to direct sunlight or high temperatures. Moreover part of the root system remains suspended in air above the nutrient flow representing a major constraint for the production of long-cycle crops (over 4–5 months) [9]. However researchers and scientist develop multilayer NFT troughs to overcome these challenges. The multilayer NFT system allows longer production cycles without clogging problems [9].

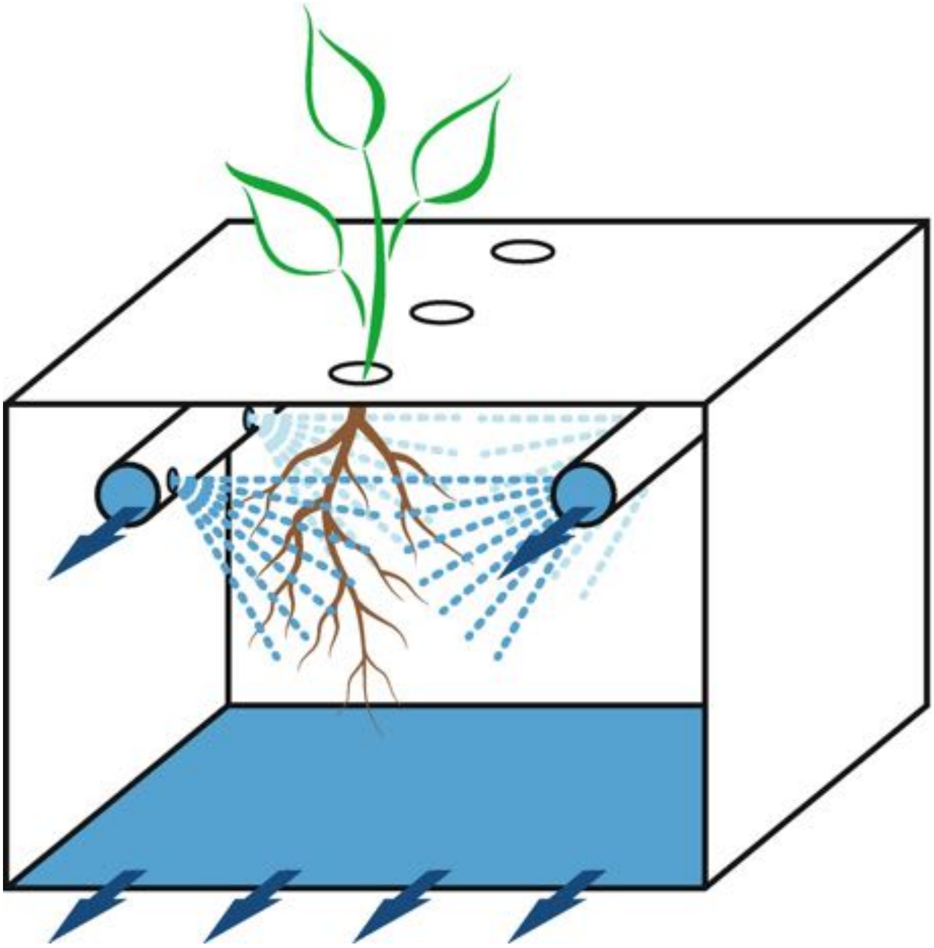
Fig. 3: NFT system



Source: *Maucieri et al. (2019) Hydroponic Technologies. In: Goddek S., Joyce A., Kotzen B., Burnell G. (eds) Aquaponics Food Production Systems.*

3_ Aeroponic: This system is defined as an enclosed air and water/nutrient ecosystem that creates the right conditions for rapid plant growth using little water and direct sunlight, without any soil or media [8]. While in DFT and NFT hydroponic systems water is used as growing medium, the Aeroponic system uses mist of nutrient solutions instead of water [6]. Hence, in Aeroponic cultivations there is no need for containers to hold the liquid solution. To this regard, this system is very efficient as it requires very little water and small spaces to be installed. Plants are then grown in boxes where their roots are suspended in the air, permitting the crown to grow upward, while the roots freely develop downwards [6]. The structure of the boxes is made with with inert materials (plastic, steel coated with plastic film, polystyrene boards) [9]. A nutrient-reach water solution is directly sprayed on the suspended roots, without the needs of pipes within the growing box. The spray duration varies from 30 to 60 seconds and the frequency depends on the cultivation period, the growth stage of the plants, the species and the time of day [9]. The closed system allow to recover nutrients at each cycle. Nonetheless, in spite of these advantages, the Aeroponic technique has been used mainly to cultivate smaller horticultural species, and it is not commonly used due to the high investment and management costs [9].

Fig. 4: The Aeroponic system



Source: *Maucieri et al. (2019) Hydroponic Technologies. In: Goddek S., Joyce A., Kotzen B., Burnell G. (eds) Aquaponics Food Production Systems.*

Advantages and Disadvantages of the Liquid Hydroponics

From the analysis of the three main Liquid Hydroponic systems it is possible to report a series of advantages and disadvantages that must be taken into consideration when developing Building-Integrated Agriculture projects. The list showed in Table 2 takes into consideration costs, water usage, management issues, and the versatility of the systems.

Concerning water efficiency, all three methods can be operated in closed system recycling the nutrient solution, whilst the Aeroponic system seems to be more efficient regarding water consumption. Nonetheless, DFT and NFT systems are easier and cheaper to manage. In the NFT system the automatization with dosing machine can dramatically cut labor costs guaranteeing optimal growing conditions, while in DFT plants are floating over a nutrient solution limiting maintenance work.

In conclusion, the NFT system permits to have a more precise agriculture, the DFT system requires low investment and operational costs while the Aeroponic system requires very little water and small spaces to work, making it more versatile and adaptable to different places and locations.

Table 2: Advantages and Disadvantages of Liquid Hydroponics

	Advantages	Disadvantages	Use
DFT	• Raft materials permit high insulation values making the system thermally stable. • Containers and ponds can be made of every dimensions and customized following growers needs. • Irrigation operations are easy to handle minimizing costs and management work.	• To be efficient DFT rafts must be spread throughout the entire surface of the GH, limiting space usage efficiency. • Large units are heavy and and presents added expense and challenge to raising off of ground level. • Large, heavy units might be hard to move and cleaning operations are difficult. • As plants are immersed into the nutrient solutions there is no capacity for precision irrigation.	Short-cycle crops.
NFT	• Automatization with dosing machine that can guarantee optimal growing conditions reducing labor & management costs. • Low water and nutrient consumption due to the closed-system. • Easy to clean the roots and the channel compared to the DFT system. • Regular feeding and flushing prevents localized salt build-up in the root zone and maintains uniform root zone pH and conductivity.	• Low water levels make the system susceptible to pumps failure problems such as clogging and failure in the power supply. • High susceptibility to temperature variations: temperature fluctuations in the nutrient solution can cause plant stress followed by diseases.	Short-cycle crops.
Aeroponic	• Fast plants growing due to the constant access to water, nutrients and oxigen. • Less need for nutrient and water as absorption rates are higher. • Requires little space and growing boxes can be adopted and tailored to growers needs.	• High investments and managing costs. • Advanced technical knowledge required as a certain level of competency is required in running the Aeroponic system. • The box where the roots are suspended needs constant cleaning otherwise diseases may strike the roots.	Smaller horticultural species.

Final considerations on the hydroponic systems

After the analysis of the case studies and of the literature related to the hydroponic cultivation methods, it emerged that application of soil-less hydroponics may take many forms and have different purposes, advantages and disadvantages. Depending on the ZFarming project, hydroponic solutions may change drastically. Aggregate or Liquid Hydroponics are both used in building-integrated agriculture. A synthesis of the different methods and applications of the hydroponic systems has been reported in Table 3. It is important to stress that not all hydroponic methods have been reported in this research, which focused on those that were mostly used in the selected case studies. As architects might have limited knowledge of these systems, the cooperation with agronomists and engineers is vital to increase chances of success in BIA projects.

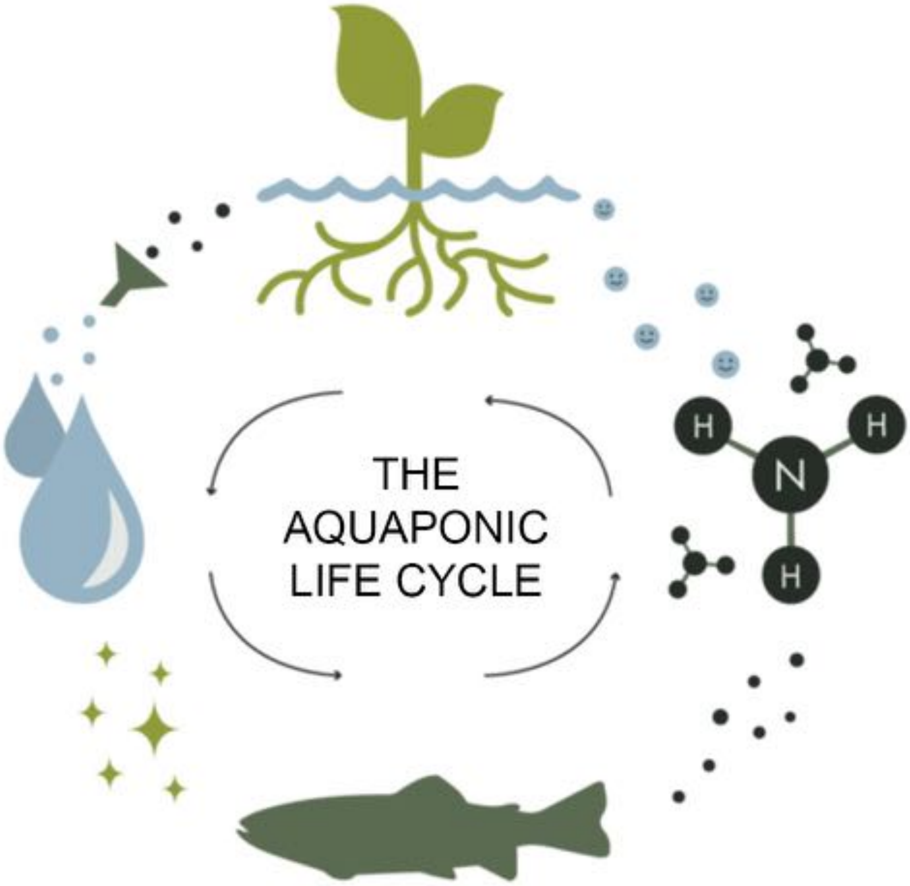
Table 3: Characteristics of the Hydroponic systems

Macro-Categories	Methods	Characteristics
Operational systems	Open System	Each cycle plants are fed with new nutrient solutions. The drained solution is not recycled from the cultivation modules.
	Closed-loop System	The drained nutrient solution is recovered and put back into the system. The solution is adjusted with lacking nutrients and brought to the right EC level.
Growing media	Substrates	Used substrates may be: • Organic substrates • Inorganic substrates • Synthetic substrates.
	No substrates - Liquid Hydroponics	Growing methods are: • DFT - Deep Flow Technique • NFT - Nutrient Film Technique • Aeroponics.
Water supply	Continuos	• DFT - Deep Flow Technique • NFT - Nutrient Film Technique
	Periodically	• Aeroponics.

1.1.2 The Aquaponic system

The Aquaponic system is a relatively new technology, emerged in the USA in the early 1970s, that combines recirculated aquaculture (the activity of breeding, raising and harvesting fishes) with hydroponic vegetable, flower, and herb production [17]. Hence, Aquaponics can be defined as an integrated agri-aquaculture system that combines animal and plant culture technologies [6] aiming to create symbiotic relationship between the plant and the fish. The synergy between the two systems is achieved by using the nutrient-reach waste coming from the fish tank to feed the plants in the connected hydroponic system; in return, the hydroponic system works as a bio-filter removing gases, acids, and chemicals, such as ammonia, nitrates, and phosphates, from the wastewater [6]. Aquaponic is then an ideal circular system where the outputs from fish breeding processes are used as nutrient inputs for plant growth in the hydroponic system, which in turn cleanses the wastewater that is later pumped back into the fishing tank (Fig. 4.1). For this reason, it has been recognized as one of "ten technologies which could change our lives" as it shows great potential to revolutionize the way we feed growing urban populations [18].

Fig. 4.1: The Aquaponic cycle



Source: *Orsini et al. (2019) UrbanFarm 2019, Projects for the former Zanussi area in Conegliano* [19].

To this regard, Aquaponics has seen an increasing interest in the scientific community, with a growing number of publications and academic researches in recent years, documented by a high ratio of Google to Google Scholar search results in 2016 [20]. The success of Aquaponic can can be explained as researchers envision that this system offers several opportunities for sustainable food production by achieving the 3Rs (reduce, reuse, and recycle) [6]. As reported in literature, some of the benefits of Aquaponic systems are [21]:

- Cleaning water for the fish habitat;
- Providing organic liquid fertilizers that enable the healthy growth of plants;
- Providing efficiency since the waste products of one biological system serves as nutrients for a second biological system;

- Saving water since water is re-used through biological filtration and recirculation. This feature is attractive particularly in regions that lack water;
- Reducing, even eliminating, the need for chemicals and artificial fertilizers;
- Resulting in a polyculture that increases biodiversity;
- Supplying locally-grown healthy food since the only fertility input is fish feed and all of the nutrients go through a biological process;
- Facilitating the creation of local jobs;
- Creating an appealing business that supplies two unique products from fresh vegetables to fish in one working unit.

In-spite of the advantages brought by Aquaponic systems, their application continue to be at the experimental stage [6], with still limited applications compared to hydroponics. This may be due to the fact that the required technologies technologies are relatively complex, requiring the mutual dependence of two different agricultural products calling for intensive management operations [21]. Furthermore, fish waste nutrients are different from the specific nutrient solutions that are used in hydroponic system. This may result in lesser yields and impede certain crops to be grown in Aquaponic as they lack fundamental minerals such as Potassium or Phosphorus.

It is important then that urban aquaponic farms balance the higher production costs with the competitive marketing and distribution advantages that urban locations offer [22]. As for many ZFarming operations, the greatest benefit for locating aquaponic systems within cities is that a growing consumer market may be interest in fresh, high-quality and locally grown produce [22]. Plus, unlike hydroponics, aquaponics can also produce fish improving possible revenues by selling it in an urban setting which often has diverse dietary needs [23].

Fish culture technologies

A fundamental aspect of Aquaponic systems is the design of the integrated aquaculture method. Most appropriate fish culture technologies must, in-fact, allow adequate nutrient accumulations to meet plant nutrient requirements [17]. Only high fish waste accumulation has the potential to produce water nutrient concentrations that can be considered efficient in the integrated hydroponic system [24]. To this regard Recirculating Aquaculture System (RAS) principles are wildly applied in aquaponics as fish here is kept and grown in controlled volumes of water, with low daily water replacement rates [17]. RAS is an intensive fish production system which use a series of water treatment steps to depurate the fish-rearing water and facilitate its reuse [25]. It generally includes [25]:

(1) Devices to remove solid particles from the water which are composed of fish faces, uneaten feed and bacterial flocs;

(2) Nitrifying bio-filters to oxidize ammonia excreted by fish to nitrate

(3) Gas exchange devices to remove dissolved carbon dioxide expelled by the fish as well as/or adding oxygen required by the fish and nitrifying bacteria

The intensive RAS system allows fish waste accumulations that approach those required to efficiently hydroponically culture the plants [26] making RAS fish culture the only real appropriate method to apply for fish culturing components in an aquaponic context [17]. Thus, the primary characteristic for aquatic organisms to be productive in aquaponics is the ability to tolerate high population densities and high levels of total suspended solids, nitrogen, phosphorous and potassium [27]. Generally, fish should not be stocked higher than 0.06 kg/L, although species which can thrive close to this density level are ideal for aquaponics [28]. For this reason, the most commonly used fish species in aquaponics are [28]:

Nile tilapia: Arguably the most common aquaponics species as they are ideal candidates are very easy to breed and will thrive even in sub-prime water conditions. Tilapia are omnivorous meaning they could eat algae, among other things, helping the whole system to stay clean. As they require warm water, a greenhouse system is suggested to properly operate the aquaponic system. Out of the hundred species that are part of the tilapia family, the Nile tilapia is the most extensively farmed [28], due to its rapid growth and good size at harvest.

Carp: In previous centuries carp was one of the most farmed fish species across the world and it remained popular in parts of Eastern Europe and Asia. Nowadays, aquaponics and other agricultural innovations are turning more people's attention on these food eating fish. Omnivorous, carp thrive in a wide range of water conditions, making them an optimal choice if the Aquaponic system is set in countries with highly variable weather conditions. Moreover, as carp have high reproductive capabilities, it would be possible to rear successive generation form the starter stock, reducing investment costs.

African Catfish: Catfish are one of the best-farmed fish and are popular for their taste. Catfish are bottom feeders and valuable scavengers that can withstand a wide range of water conditions. They are not territorial and easy to breed and raise. Catfish thrive at a similar temperature to tilapia and require a pH of 7 -8. They grow relatively fast and can be harvested within three months [29].

Trout: Trout are the perfect fish for indoor and outdoor systems because they have an excellent temperature range. Trout prefer colder water and thrive in temperatures ranging from 13 - 20 °C making them ideal for a cooler environment. Trout grow slowly and reach about one pound in 4 years in the wild [29].

The integration with the hydroponic systems

The three most common hydroponic systems used in aquaponics are varying forms of: i) deep flow technique (DFT) or floating raft technique, ii) media filled grow beds, or iii) nutrient film technique (NFT) [30].

NFT: In a 2006 study [31] it was found out that when NFT systems are integrated with Aquaponics they have a lowest yields compared with DFT systems. This cause a less absorption of the nitrate (20% less than in DFT systems) probably caused by the fact that a lower percent of roots is in contact with the nutrient solution. Despite that, NFT is commonly used in commercial Aquaponics as it is easy to manage and requires low investment costs [32].

DFT: It is probably the most common system used in Aquaponics because its low maintenance requirements [28]. This system maximize root water contact, and allow to support a great number of plants in spite of minimal materials usage [28]. Compared to the NFT and the media systems, DFT remove most of the nitrate contained in the fish waste nutrient solution. Compared to media systems, it is considered to be more sustainable, as it doesn't require inert materials to support plants [33]. Another advantage of this system is that the higher water efficiency, even though it requires more water to operate. Love et al. [34] demonstrated that a DFT Aquaponic system used only 1% of its total system water per day.

Media culture: This system is commonly used for small-scale, research operations [28]. This is due to the fact that media culture requires periodic maintenance as the substrate is subjected to clogging issues, creating uneven fertigation in the hydroponic system [28]. In this case, growers need to manually clean the system and even remove and replace the growing medium, resulting in increasing operational costs. Nonetheless, media culture allow to grow a greater number of plants in the Aquaponic system as media beds provide better stability for roots to grow [35]. Furthermore, substrates materials allow physical filtration and thus removing the needs for bio-filters installation [30].

Crops choice

Plants that can be grown in Aquaponic systems strictly depends on which hydroponic method is used. Although, leafy vegetables have been the preferred crop to grow in aquaponic systems, as they grow well in nitrogen concentrated water, have a short growing period, do not have high nutrient requirements and there is generally a high demand for them globally [36]. For instance, flowering crops are considered more valuable on the market, but they are much harder to grow in Aquaponic system as they require Phosphorus and Potassium to grow, which are not provided by the fish waste nutrient solution [28]. In a 2015 study [37], established the crops that were commonly grown in commercial Aquaponic facilities: basil (81%), salad greens (76%), non-basil herbs (73%), tomatoes (68%), *Lactuca sativa* (head lettuce) (68%), *Brassica oleracea* (kale) (56%), *Beta vulgaris subspecies cicla* (chard) (55%), pak choi (51%), *Capsicum annuum* (pepper) (48%), and *Cucumis sativus* (cucumbers) (45%).

Final considerations on the Aquaponic system

Table 4: Characteristics of the Aquaponic system

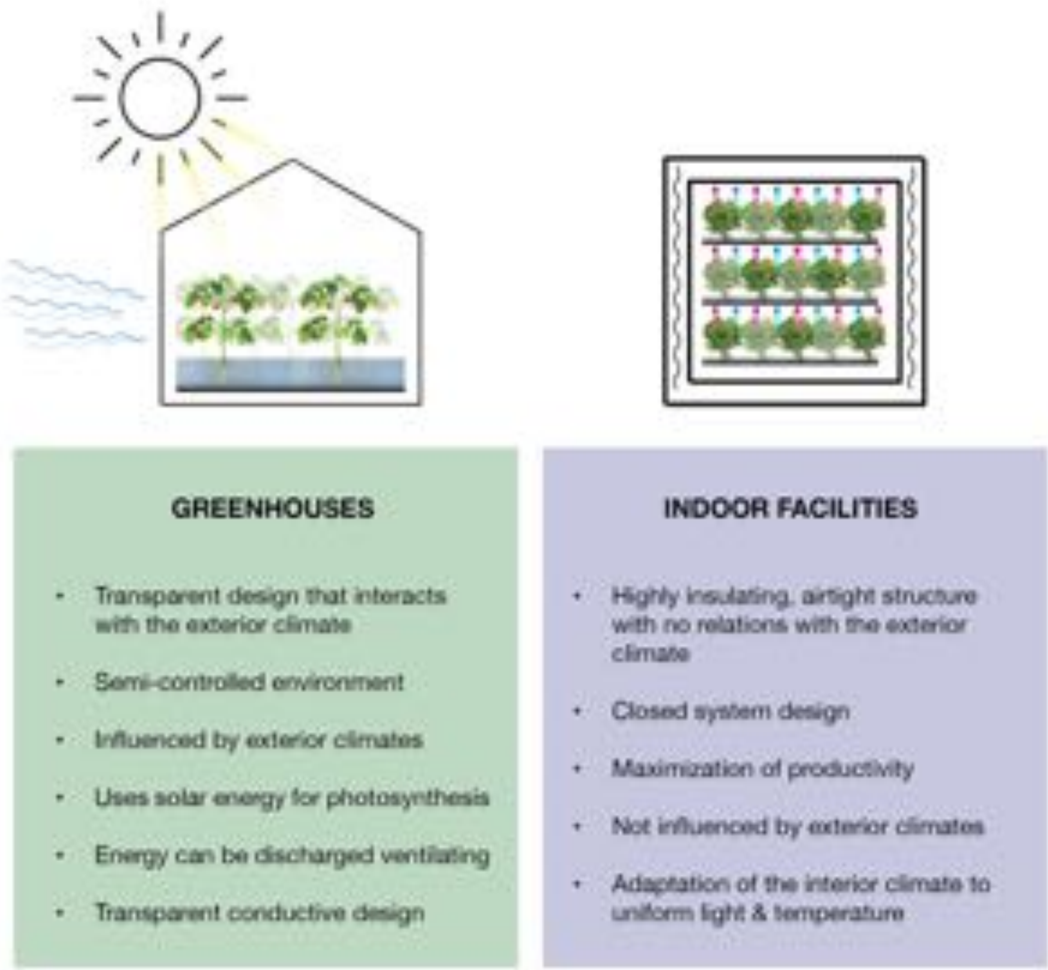
Macro-Categories	Methods	Characteristics
Fish culture	Intensive RAS	It allows to have high fish waste accumulation. High water nutrient concentrations are vital to the efficiency of the integrated hydroponic system.
	Fish species	Tilapia, Carp, Catfish and Trout are the most commend reared fish. Fish species must grow well in high density conditions,
Hydroponic methods	NFT	Easy to manage and requires low investment costs. Production yields is lower than DFT.
	DFT	High water efficiency. Most common hydroponic methods used in commercial Aquaponics.
	Media culture	Used for small-scale operations. Allow to grow a greater species of crops. Requires periodic maintenance.
Crops choice	Leafy Greens	Grow well in nitrogen concentrated water, have a short growing period, do not have high nutrient requirements.

Similar to the hydroponic system, the Aquaponic method has a variety of applications. Differently from the hydroponic, the Aquaponic system has the advantage of producing fish other than plants. This can result in different business models and eventually more revenues, opening new market opportunities.
Nonetheless, crops grown in Aquaponics are influenced by the high concentration of nitrate in fish waste water, and nutrient solutions might not be adjusted for certain crops, limiting the applications of Aquaponic systems. Furthermore, Aquaponics require high investment costs and a deep knowledge on the technical requirements of the system other than a periodic maintenance.

1.2 Enclosures of the soil-less systems: plant factories vs greenhouses. A review

Both Aquaponics and Hydroponics require architectural structure in order to be operated. To this regard, the term *Enclosure* defines the characteristics of the structures that host the growing systems. Transitioning from soil-based agriculture to soil-less practices, in-fact, requires permanent facilities that allow year-round crops, regardless of the local climate. This process is known as controlled environment agriculture (CEA) and includes two main systems: (i) greenhouses and (ii) indoor growing facilities (Fig. 5). The main difference between these two systems is how they interact with the exterior contexts: greenhouses have a translucent design, that allows solar radiations to pass through the envelope and affect plants growth; indoor facilities (or plant factories) are air-tight structures that do not permit any relation with the outside climate. Here, plants are grown through LED lights, which will induce photosynthesis processes.

Fig. 5: Differences between Greenhouses and Indoor Facilities



Source: Own work

In addition to controlling the indoor climate, CEA has the potential to dramatically reduce the risk of crop loss to natural calamities and the need for herbicides and pesticides [22]. Both Hydroponics and Aquaponics require controlled growing conditions to guarantee optimal productivity.

2.1 CEA typologies

Reviewing the literature and the case studies, it was possible to categorize different CEA typologies (Table 5), based on construction systems, levels of technological control, passive climate control strategies, and energy sources to achieve an appropriate indoor climate [22]. The classification here reported differentiates four categories of greenhouses - (i) medium-tech greenhouses, (ii) passive solar greenhouses, (ii) high-tech greenhouses, (iv) and rooftop greenhouses [22] - from one macro-category of indoor farming.

Table 5: Controlled Environment Agriculture typologies

CEA Type	Characteristics	Advantages	Disadvantages
Medium Tech Greenhouse	Intermediate levels of technology to control indoor climate. The limited control capacity of indoor climate make them more suitable for temperate climates.	Low investment costs. Uses mainly passive climate control strategies reducing production carbon footprint.	Not suitable for cold or excessively warm climates. Cladding materials may be often replaced due to constant UV exposure.
Passive Solar Greenhouse	Uses high insulated north facing was as thermal mass to provide heating in the greenhouse. The sun-exposed facade is full glass and solar energy is the only source of light and heat in the GH.	Designed to absorb and release heat, reducing to zero the need for cooling and heating devices. The design can be adapted to several locations.	It is not suitable for cold climates. Due to its weight and characteristics, it is not advised to integrate within buildings.
HighTech Greenhouse	It is designed to grow crops with soil-less methods, taking advantage of technical development to adjust inner climate conditions based on plants' needs.	Fully controlled internal environment which allows to maximize food production. Can be used in BIA both on rooftops and facades, allowing high production in small urban spaces. Can be operated anywhere.	High investment costs. Depending on the energy sources used to operate the technological system it may have a non-sustainable carbon foot-print.
Rooftop Greenhouse	Refers to greenhouses built on host buildings. It can be integrated both in retrofitting and new construction projects.	Can create resource flow exchange with the host building. May revitalize underused space in urban settings while providing locals with fresh food.	High investment costs. Commercial greenhouses may struggle to produce revenues.

Indoor Facilities	Air-tight, highly insulated structures that have no relationship whatsoever with the external environment.	Stable production all-year-round that can guarantee 10-20 yields per year. Easy to integrate in existing buildings, with the possibility to create new profits and generate new job opportunities. Good design and the implementation of renewable resources use may result in high yield with minimum carbon footprint.	High investment and labor costs. High energy consumption which may result in unsustainable practices. Limited production to leafy greens. Uncertain revenues.

Greenhouse typologies

Greenhouse horticulture is considered a (semi-)controlled environment. Greenhouses mainly use solar energy for photosynthesis [38]. Passive strategies can be used to heat the greenhouses through solar radiations and to cool them down through ventilation. In more advanced systems, heating and cooling devices can be used to achieve a fully controlled environment. The main characteristic of all greenhouse typologies is the translucent design, which allow thermal exchange with the exterior climate. To this regard, the relation between the costs (heating and cooling) and benefits (solar radiation) of greenhouse production largely depends on the latitude and external climate conditions of the site [38]. Depending on the CEA concept, it is possible to divide the greenhouse typologies into four categories:

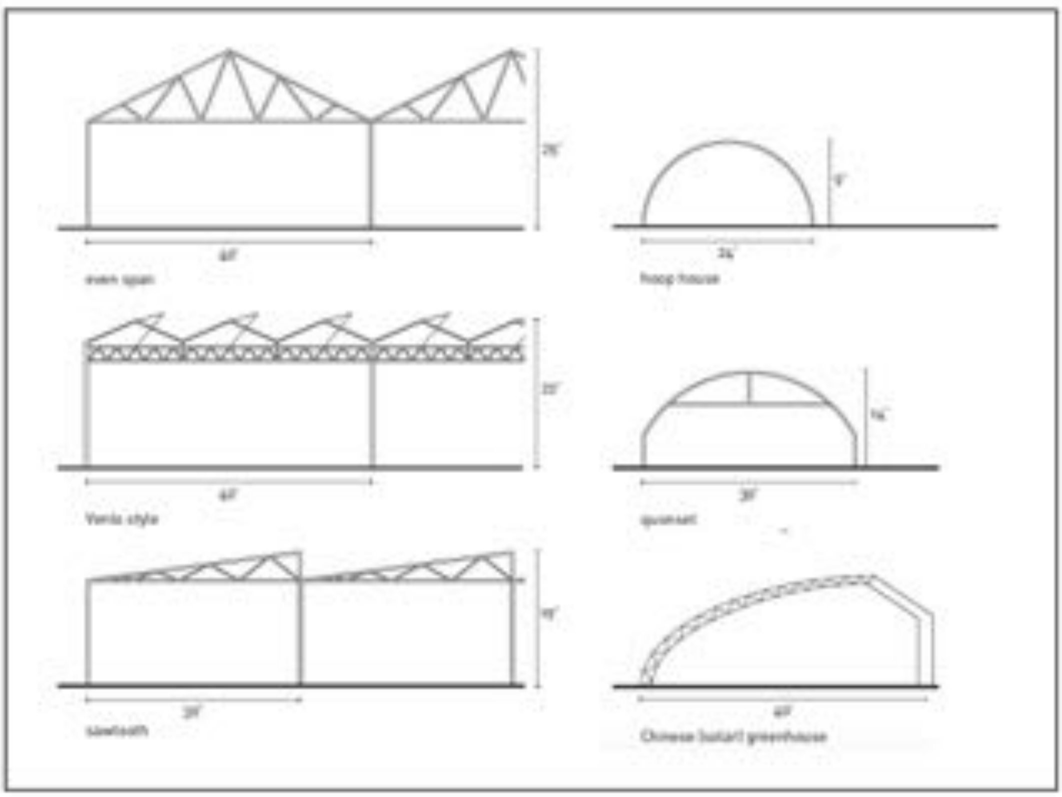
1_ Medium Tech Greenhouses: Medium-tech commercial greenhouses offer a blend of performance and cost-effectiveness as they are cheaper than high-tech commercial greenhouses and at the same time offer better performance than low-tech commercial greenhouses. Greenhouses with intermediate levels of technology to control the indoor climate are usually covered with double polyethylene film (PE) or rigid plastic panels, such as acrylic panels (PMMA) and polycarbonate panels (PC) [22]. The installation of these greenhouses is generally less expensive than more technological ones. However, it is possible that cladding materials need to be often replaced due to their deterioration caused by the constant exposure to UV radiation [39]. These greenhouses use mainly passive climate control strategies, relying mostly on solar radiation, simple shading systems, and natural ventilation [22]. Their main purpose is to protect crops from extreme climatic events, and the use of soil-less systems might protect crops to some pathogens found on soil-based agriculture. The limited ability of these greenhouses to control plants' growing conditions make them more suitable for temperate climates, with mild winters and moderate summers [22]. The architectonic structure (Fig. 6) of medium tech greenhouses may include freestanding or gutter-connected Quonset (Nissen hut type), hoop house (polytunnel) and even-span greenhouses [39].

2_ Passive Solar Greenhouses: All greenhouse types are thought to be lightened by solar radiations, but in this case Passive Solar Greenhouses are designed to be heated by solar energy only [39]. The architectonic design is strongly influenced by the necessity to absorb and release heat. For this reason, highly insulated north facing walls must act as thermal mass, while south-facing facades are made out of glass and generally they are arc-shaped blending into one single element with the roof. Solar energy is the only source of light and heat for crop production in these greenhouses [39].
The exposure to the sun determines the light conditions inside the greenhouse, which vary according to the season, latitude, greenhouse structure, quality and aging of the plastic film, and

duration of daylight [39]. Considering their characteristics, passive solar greenhouses are less likely used in building integrated agriculture.

3_ HighTech Greenhouses: These greenhouses are created to fully control inner climate conditions, favoring optimal plants' growth. The term high-tech refers to the technological requirements needed to run the greenhouse. High-tech greenhouses rely almost exclusively on soil-less recirculating systems like hydroponics and aquaponics. Temperatures, irrigation, nutrients concentration in the water solution, shading, lightening and CO2 enrichment are regulated by automated control systems [39]. Thus, this type of greenhouse can potentially be operated anywhere, as long as the revenue produced pays for the high energy and operation costs in extreme climates [39]. Nonetheless, if operated in northern latitudes, with reduced sun exposure and in a cold climate, this typology may not be environmentally sustainable due to the energy consumption used for heating and supplemental lighting [38]. To this regard, the exact environmental footprint of a high-tech greenhouses strictly depend on the location of the project and on the quality of energy sources used for supplemental heat and light [39]. Typical high-tech greenhouses are steel or aluminum structures, often erected as large horizontal arrays [39]. It is important to create large floor areas and small exterior envelope. The ratio between floor area and envelope improves the environmental performance of the greenhouse [39]. In the analysis of the case studies, it was possible to see how high-tech systems are largely used in rooftop greenhouses and in food-integrated facades. This can be explained considering the small space availability in urban areas and the consequent necessity to maximize food production. From a structural point of view, when high-tech greenhouses are positioned on rooftops, it is possible to distinguish them by the shape of their roof, which depends from the location, altitude and sun angle. These shapes include even-span roofs with two slopes of equal pitch and equal length; Venlo-style greenhouses, whose low-profile roofs have small pitch angles and ridge ventilation; and uneven span or mono-pitch roofs connected into a multi-span, sawtooth design (Fig. 6) [39].

Fig. 6: Greenhouse typologies construction systems



Source: *Proksch, Gundula. (2017). Creating Urban Agricultural Systems: An Integrated Approach to Design*. [39]

4_ Rooftop Greenhouses: This type mostly refers to high-tech greenhouses built on host buildings, and can be applied both in retrofitting and new construction projects and in recent years, rooftop greenhouses have seen an increasing success. The success of this typology is connected to the high land costs in urban settings, which brought urban farmers to look for unused spaces within cities. For instance, connecting a greenhouse to an existing building is one possible strategy to revitalize underused spaces and provide locals with fresh food production. As it was noticed in the analysis of the case studies, most of realized ZFarming initiatives fell in the category of rooftop greenhouse. Both research facilities and commercial greenhouses are used within this typology. The possibility to create new flows of resources between the integrated rooftop greenhouse and the host buildings is now a hot topic in the research of BIA. For instance, the Institute of Environmental Science and Technology (ICTA) and the Catalan Institute of Paleontology (ICP) at the Autonomous University of Barcelona (UAB) are carrying on several researches assessing the benefits of integrated hydroponic rooftop greenhouses.

Indoor facilities (for Plant Factories with Artificial Lighting)

Indoor farming is a closed production system where the enclosure is designed to maximize production density, productivity and resource use efficiency [38]. High productivity can be achieved by creating indoor climate conditions that favor plants' growth. Thus, the use of technical devices is fundamental to uniform lighting, temperature and relative humidity [38]. In order to reach perfect indoor climate conditions, it is crucial to minimize interactions with the exterior climate. Limiting these interactions can also benefit the efficient use of energy, water and CO_2 [40]. Due to its characteristics, indoor farming is particularly suitable for BIA initiatives, as it can maximize production capacity in relatively small urban spaces, exchanging resources with the hosting buildings. Plus, PFALs offer new design solutions for the retrofitting of abandoned buildings, repurposing them creating new job opportunities.

For these reasons, this growing method has seen increased interest in the past years, raising conflicting opinions in practitioners and researchers [41]. Most opponents of PFALs initiatives tend to stress the limitation of a system that only uses artificial lightening to grow plants, arguing that this will result in an unsustainable use of resources with a worst carbon footprint than traditional agriculture. Plus, a diffuse skepticism is connected to the high investment and labor costs required to start a PFAL that may result in zero or very little profits for urban growers, possibly discouraging young entrepreneurs to undertake similar initiatives. However, indoor farming is constantly evolving and new researches and projects are outweighing the disadvantages of the absence of solar energy. For instance, experiences like the SkyGreens in Singapore seem to have reached economic viability with the development of technically sophisticated, highly productive, energy-efficient, and reasonably priced LED grow lights [39]. Hence, to be sustainable PFALs should satisfy the following six conditions [41]:

(i) The entire food chain, from production to consumption, should be resource saving and have low CO_2 emissions;
(ii) Use of water must be reduced as well as the use of chemical pesticides and of fossil fuels for heating and cooling, minimizing the release of environmental pollutants;
(iii) Resource use efficiency must be optimized, with initial investments on renewable energies;
(iv) Production stability must be implemented and deliver high quality crops and high yield all year round;
(v) Must foster social inclusion creating new employment opportunities;
(vi) International technology transfer must be facilitated through the development of standardized systems.

The design of PFALs enclosure and the chosen system components should aim to satisfy these conditions, providing growers with production spaces that are easy to manage, completely insulated from the exterior climates and adaptable to environmental and social changes. In order to achieve that, six main structural elements must be taken into consideration when designing indoor facilities [42]:

1. The production spaces must be air-tight. The envelope must be thermally well insulated and the structure covered with opaque walls.
2. Multilayer hydroponic culture beds should be disposed in a way to occupy the internal space in the most efficient way to maximize production surfaces. Every layer should be equipped with fluorescent or LED light sources, directly illuminating each culture bed.
3. Heat pumps should be used mainly for cooling and dehumidification, in order to mitigate the heat generated by the growing lamps and eliminate the vapor produced by the plants. Fans for forced air circulation should be provided to achieve uniform air distribution.
4. A CO2 delivery unity should always be provided in order to reach CO2 concentration of 1000 ppm in the growing room, favoring plants' photosynthesis processes, maximizing the production.
5. A nutrient delivery unit should be installed.
6. A climate control room should be designed in order to alway keep indoor environment to optimal growing conditions. It is important to integrate the climate control room with a fertigation chamber that can constantly monitoring water pH, electric conductivity (EC) and nutrient contents in the nutrient solution.

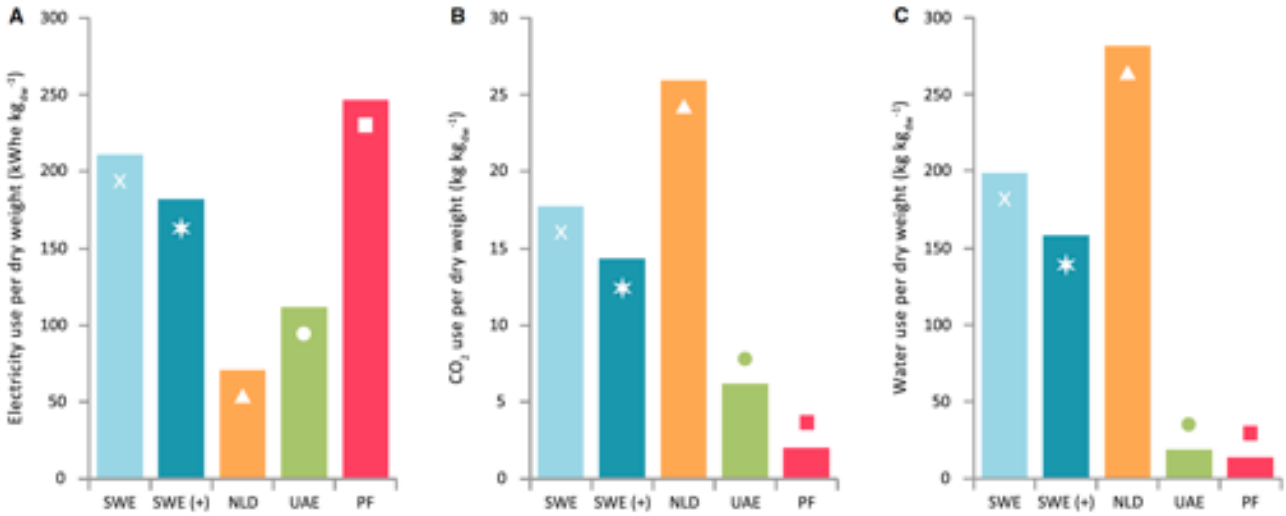
Use or resources comparison between greenhouses and plant factories

A recent study by Graamans et al. (2018) [38] assessed the different performances in lettuce production of four greenhouses and plant factories in different climates and locations. The simulation was run in three different settings: in Sweden (SWE) - where two greenhouses were considered, one with artificial lightening and the other without - in The Netherlands (NL) and in the United Arab Emirates (UAE) - both without artificial lightening. As emerged from the simulation, while greenhouses had different energy, water and CO2 requirements, the production and the use of water and CO2 are quite similar in all three plant factories in spite of the different climate conditions. The result of this study showed how the optimization and uniformity of the interior leads to a higher production of dry matter in plant factories in comparison with greenhouses. Nonetheless, the sustainability of this production is strongly energy requirements of these systems.

Concerning energy use, simulations showed that the energy efficiency of plant factory is considerably higher than in greenhouses, although they require a larger input of purchased energy. Most of purchased energy in plant factories is used to power the artificial illumination, however, high energy loads are used for heating the greenhouses in the NL and in SWE and for cooling the greenhouse in UAE. To this regard, the total amount of equivalent energy required for the production of dry matter in plant factories is actually lower than in greenhouses at each location, however, due to their translucent design, greenhouses need to purchase less energy than PFs. Meaning that 'direct use of solar energy has a greater impact on the total energy requirement than an efficient use of energy' (Fig 7A). Hence the authors' conclusions reported that presumably plant factories are more suitable than greenhouses for lettuce production at higher latitudes. This is proved by the fact that artificial lighting seems to improve the energetic performance of the Swedish greenhouse. On the other hand, the availability of free solar energy in hot and arid climates saves more electricity the is needed for cooling, suggesting against the use of PF in these locations.

Other resources, like water and CO2, might determine the viability of PFs projects. Of course, closed-systems can optimize the use of water, making PFs more efficient reducing up to 95% water consumption in respect to semi-open systems [38] (Fig. 7C). Same goes for CO2 efficiency, as it is strongly influenced by ventilation. Air-tight close environments in PFs do not require same natural ventilation as greenhouses (especially in hot climates) allowing to reduce CO2 use for production up to 92% [38] (Fig. 7B).

Fig. 7: Resource use for electricity (A), CO2 (B) and water (C) per dry weight of the plant factory and greenhouses



Source: *Luuk Graamans, Esteban Baeza, Andy van den Dobbelsteen, Ilias Tsafaras, Cecilia Stanghellini, Plant factories versus greenhouses: Comparison of resource use efficiency.* [38]

Explanatory table

Code	Location	Typology	Lighting	Cooling
SWE	Sweden	Venlo Type	Natural	High pressure fogging system + natural ventilation
SWE (+)	Sweden	Venlo Type	Artificial	High pressure fogging system + natural ventilation
NLD	The Netherlands	Venlo Type	Natural	High pressure fogging system + natural ventilation
UAE	United Arab Emirates	Venlo Type	Natural	Active cooling
PF	Refers to plant factories in all three locations	Closed System	Artificial	Water cooling + climatisation system

Finally, it is possible to say that the production of dry matter, as well as viability of PF facilities, strongly depends on the location, the production methods and the construction design, which determines the relation with the exterior climates. In all the three locations, greenhouse appear to be more efficient in terms of energy consumption even in harsh environment as Sweden and the Arab Emirates. However, the authors claim that there is not a real turning point where PFs are more efficient than greenhouses, considering that the simulations for the greenhouses in the most harsh climates incorporated characteristics of PF production such as artificial lightning, active cooling and closed system. Without the integration of these production method, production in these areas wouldn't be possible. Furthermore, PFs highest efficiency in CO2 and water consumption may balance the high energy requirements of the system, giving new growing opportunities in water-scarce regions. One more advantage of PFALs over greenhouses is the occupied land area, as stacking production on multi-layer dramatically increase production per square meter. Hence, in ZFarming projects PFALs advantages may outweigh the high energy requirements even in temperate or hot climatic areas. However, when integrating these two production systems in urban areas, it is also possible that they can work together developing new synergies, allowing a wider urban production.

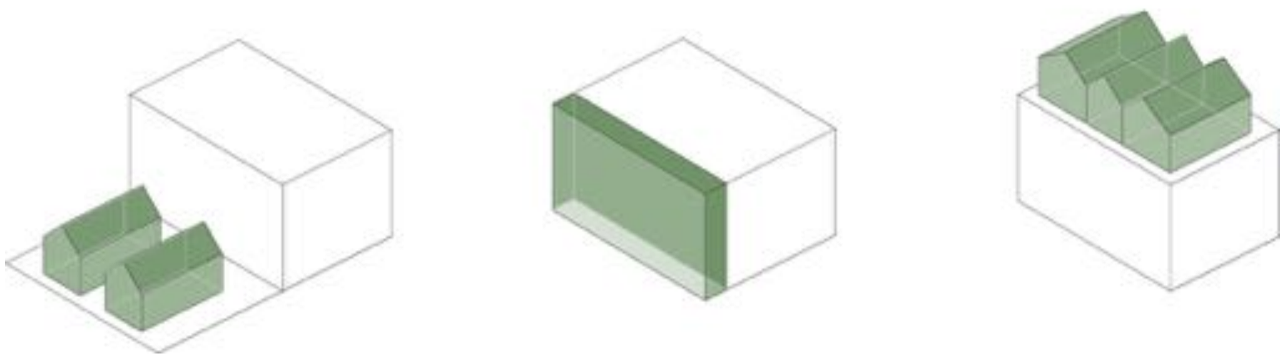
1.3 Conclusions: strategies for the integration of hydroponic systems within buildings

As emerged from the analysis of the case studies, in recent years architects, planners and engineers joined agronomists in proposing Urban Farming projects, with the aim of exploiting synergies between the built environment and the new soil-less agriculture practices [39]. In the selected case studies it is possible to see different approaches of integrating agriculture within architectural buildings, ranging from passive systems, such as container growing, to technological systems such as rooftop greenhouses, vertical facades and various types of indoor growing facilities. Each system has its way to implement the overall sustainability of the building, from mitigating roofs heat absorption, to adding extra green insulating layers to existing facades. In particular, high-tech greenhouses and plant factories are the most used systems in building-integrated agriculture, as they present the great advantage of maximizing production yields, making them more suitable for the integration in mixed-use buildings, allowing them to host multiple functions other than just food production. As it was widely stated in this research, the main difference between these two systems is the way they interact with the exterior climate. Thus, their integration in buildings highly depend on the location of each ZFarming initiative [39].

To this regard, it was noted how rooftops and south facing facades were the most commonly used spaces for active building integration with high-tech greenhouses. In most cases (i.e. the ICTA building, the Oberhausen office, the Utrecht Greenhouse Restaurant, etc.) these greenhouses operated resource efficient methods, using closed hydroponic systems, recovering rainwater, and exchanging heat with the host building. As a matter of fact, the heat absorbed by the building and transferred to the greenhouse is an efficient way to lower the production's energy demand, resulting in a win-win symbiotic relationship between the two systems. On the other hand, integrated greenhouses can also improve the environmental performances of the host buildings, providing additional insulation, cooling horizontal and vertical surfaces directly exposed to sun radiation and extracting exhaust air from the building using it to create more favorable condition for plants to grow.

All this considering, it is possible to determine strategic design solutions to optimize the integration of high-tech greenhouses in buildings. Thanks to new growing methods and technologies it is possible to see the production spaces as new components of the architectural project. To this regard, three main integration concepts were developed (Fig. 8):

Fig. 8: High-tech Greenhouse integration in buildings

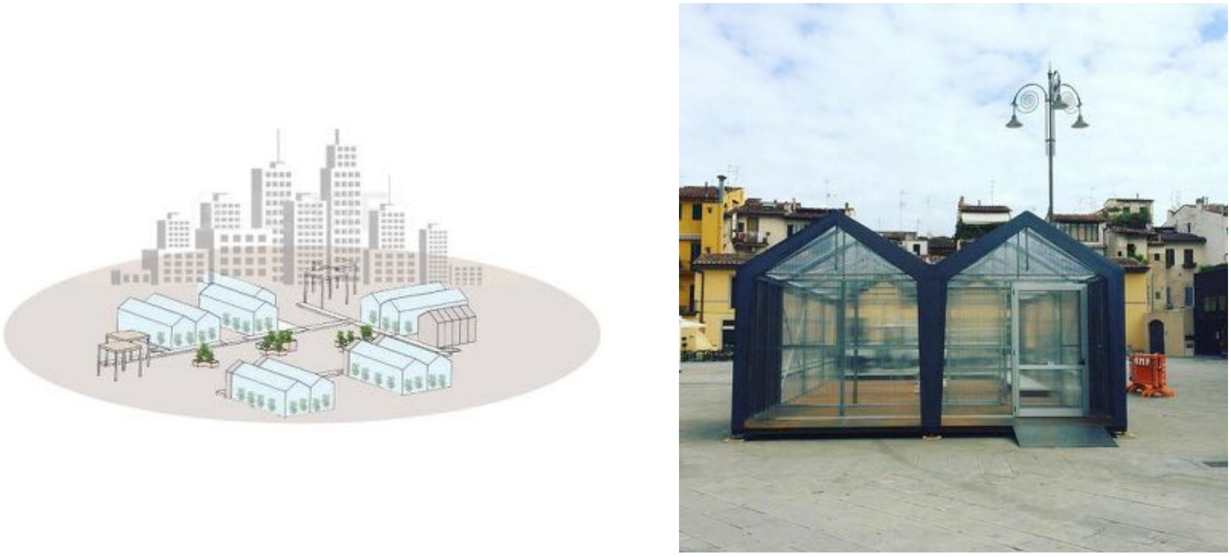


A) Private/Public open spaces **B) Sun-exposed facades** **C) Private rooftops**

Source: *Own work*

A) Private/Public open spaces: These greenhouses can be positioned both in public squares and public spaces as temporary facilities as well as in private gardens and backyards for private use. Their main objectives vary from raising awareness on food production topics in highly dense urban environments, to providing a small local production produced and consumed within the neighborhood (Fig. 9). The design of these systems must take into consideration the very limited space in which they operate, for instance, the studied state of the art projects occupied less than 70 square meters each. For this reason, these greenhouses are not to be thought as commercial facilities, however, if spread all around the city, they could consistently help with urban food production, especially reducing urban food deserts. When placed in private backyards, it would be theoretically possible to create symbiotic relationship with the host buildings, nonetheless, most examples of this type of greenhouses show how they best work separately from the surroundings. This may be due to the fact that in most cases they are just temporary infrastructure. Thus, considering these characteristics, it is suggested to implement the use of re-usable materials, easy to assemble and dismantle, limiting installation costs.

Fig. 9: UrCA (Urban Contemporary Agriculture) Project



Source: UrCA project by Chiara Casazza and University of Florence.

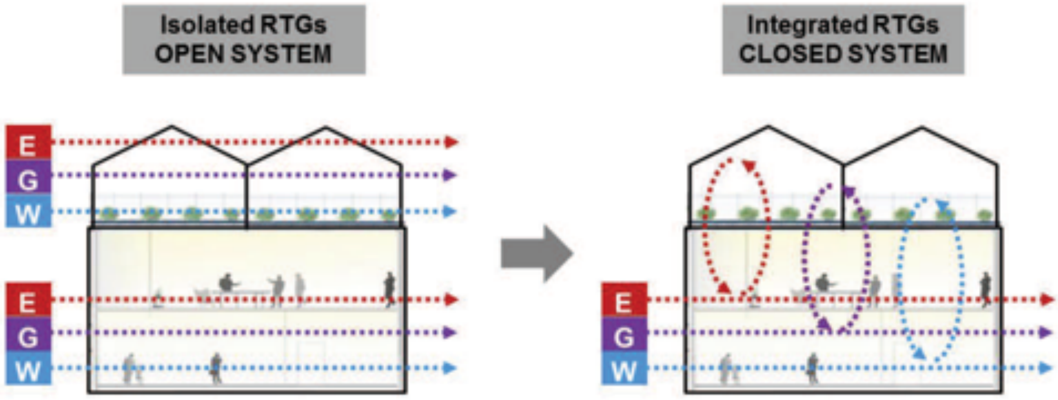
B) Sun-exposed facades: Integrating food production systems on sun-exposed facade recently emerged as a new urban farming practice. New food productive facades can be either attached to existing buildings, improving their environmental qualities, or directly integrated in the design of new construction projects. However, their application is still very new and in phase of experimentation. Most of the selected case studies are, in-fact, prototypes or conceptual projects that still struggle to see the light. This may be caused by the fact that operating facade greenhouses might be more difficult, and less productive in comparison with rooftop greenhouses. Furthermore, creating productive facades in private residential buildings may generate concern on who will run the greenhouse: residents may not have the time nor the capacity to operate high-tech systems, and be reluctant to let professional companies or researchers to walk freely in their private spaces. To this regard, designing food productive facades must take into consideration that third parties might operate them, thus, accessible working spaces should be provided to professional non-residents in order to reduce their interactions with building's inhabitants. Aside from operational issues, which might be resolved in the future with automated harvesting and monitoring processes, buildings highly benefit from the implementation of greenhouse facades in a way that the productive facade may (i) act as an extra natural insulation layer, balancing the temperatures inside the buildings; (ii) create a shadowing layer that protects the inner spaces from direct sunlight (Fig. 10), reducing facades' overheating problems especially in warm and dry climates; (iii) reduce sound pollution in urban congested areas; (iv) absorb air pollution, catching CO2 particles and relating oxygen [43].

Fig. 10: Experimentations for a productive facades. Building integrated hydroponic food market - Abu Dhabi. Kiss+Cathcart Architects

Source: *K+C Architects. [Online] Available at:* *http://www.kisscathcart.com/pdf/AbuDhabi.pdf*

C) Private/Public rooftops: Rooftop production has seen increasing interest in the past years, due to the many added benefits it brings to urban dwellers and buildings. For instance, it can dramatically increase local food production, reduce to minimum food transportation and improve local economies [44]. The great potential of rooftop greenhouses is due to two main factors: (i) rooftops have greater solar exposure than the ground below [45]; rooftops are often vacant, underused spaces in cities, which can potentially multiply production surfaces. Through the analysis of the case studies it was possible to distinguish between two main typologies of rooftop production: (i) high-tech greenhouses laid on rooftop surfaces with no interaction with the existing buildings - i.e. the Gotham Greens project in Brooklyn ; (ii) high-tech greenhouses designed to be completely integrated with the hosting building, exchanging resources such as energy, water and gaseous flows [46] - i.e. the ICTA building in Bellaterra (Fig. 11). The first typology, called Rooftop Greenhouse (RTG), is generally used when a greenhouse is placed on top on an existing building, making it difficult to connect old installations with the new ones required for hydroponic production. The second typology, called integrated Rooftop Greenhouse (iRTG), goes one step further and allow to generate symbiotic relationships between buildings and production spaces recirculating air and water and exchanging heat with the hosting building. Due to the complexity of achieving a symbiotic relationship between the two entities, architects should integrate iRTG design when approaching new ZFarming projects.

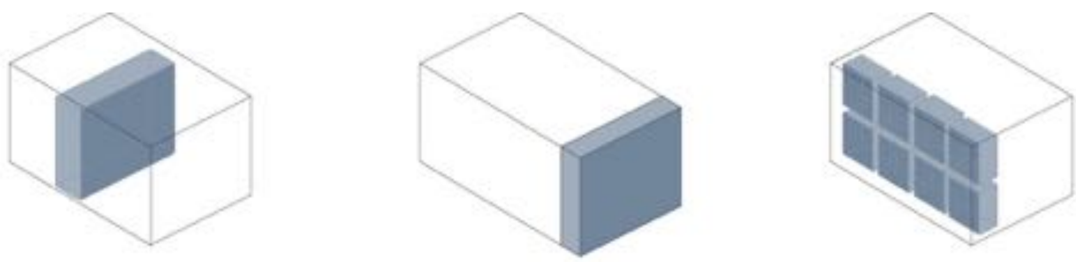
Fig. 11: Metabolism of integrated and isolated rooftop greenhouses



Source: *Sanyé-Mengual et al. [44], The ICTA-ICP Rooftop Greenhouse Lab (RTG-Lab): closing metabolic flows (energy, water, CO 2) through integrated Rooftop Greenhouses.*

While integrating high-tech greenhouses in architectural projects must take into consideration the exterior conditions, maximizing their exposure to solar radiations, indoor growing spaces rely exclusively on artificial light for plant production, opening a whole new other world of possibilities for their integration in buildings. Indoor growing spaces must have better insulation than greenhouses using different opaque envelope materials. As reported by Graamans et al. (2018) [38] this typology is better suited to extreme climates, where temperature swings are of larger concern than lighting (Graamans et al. 2018). Nonetheless, the constant research developments on the topic, make it suitable for the integration of this typology into the darkest spaces of buildings, creating new design opportunities. Taking this in mind, three main concepts of indoor farming integration were developed (Fig. 12):

Fig. 12: Indoor farming integration in buildings



A) Common hallways   B) Shadowed facades   C) Private inner spaces

Source: Own work

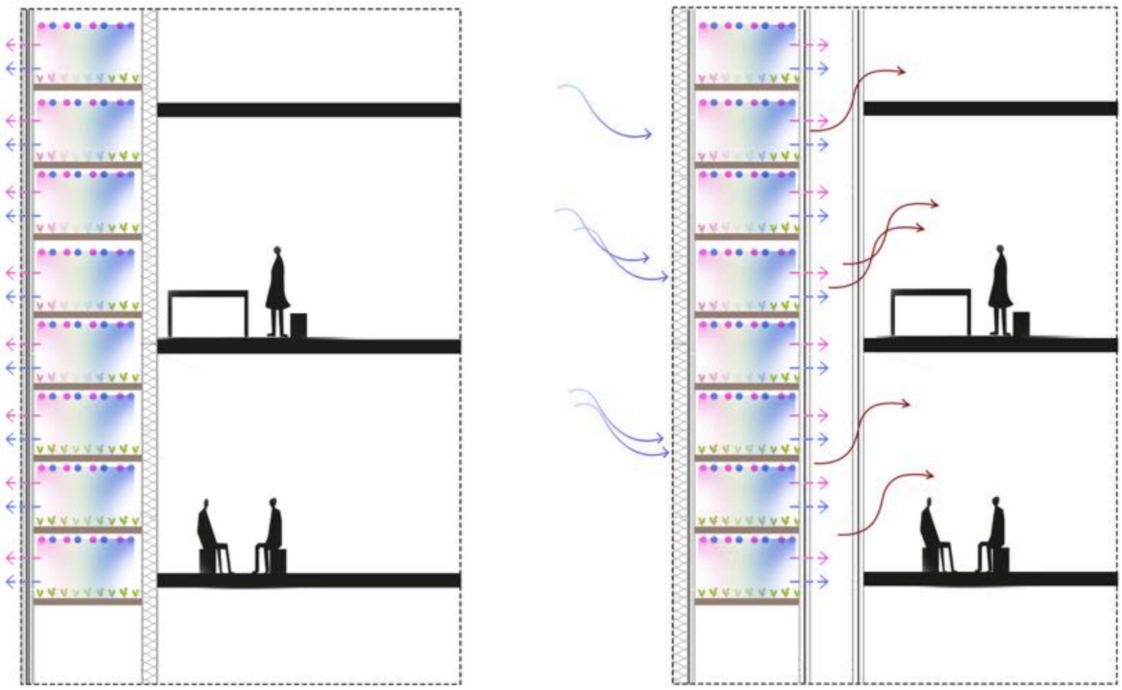
A) Common hallways: Due to the high and stable productivity of plant factories, portions of mixed-use buildings can be transformed into actual vertical farming. These spaces have the advantages of being far from external natural light sources, highly insulated by the adjacent rooms (Fig. 13) and can go up as far as the building height.

Fig. 13: Examples of indoor food production in hallways and common spaces in the Living Tower project in Amsterdam, winner of the first prize in the EcoTech Green Award 2018

Source: *Own work*

B) Shadowed facades: There are two types of integrating indoor food production on shadowed facades. The first one is to attach a new facade to an existing blind wall. In this case the two systems are completely separated and the existing wall only provides the production space with structural support. This way can be an interesting design tool to retrofit and redevelop old buildings, creating a new combination of lights and plants effect on the new facade. The second way is to design the facade as a buffer to cold temperature (Fig. 14). This type of facade has visual and practical relationship with the inner environment and can help insulating the buildings especially in harsh climates.

Fig. 14: Examples of indoor food production integrated in shadowed facades.



Source: *Own work*

C) Private inner spaces: Some best practices studied in the analysis of the case studies showed how great efforts in the research has been put into the development of design products that can be integrated in indoor spaces as furniture. The Ikea SpaceLab 10 and the Infarm project are perfect examples of this kind of research. Potentially, small farming objects can be integrated in private spaces in buildings as kitchen components, closets and even lamps (Fig. 15). Due to their limited dimensions, integrating them into the resource flow of the building may be counterproductive, nonetheless, they can be valuable elements to place in existing buildings, especially residential, to give dwellers new sources of local food, implementing education on how to manage small productive systems. One of the main purposes when designing these systems is to make them easy to operate, mostly automated where users only need to harvest when the produce is ready.

Fig. 15: Examples of small food production devices in inner spaces. 15A: Plantui; 15B: IKEA Farm

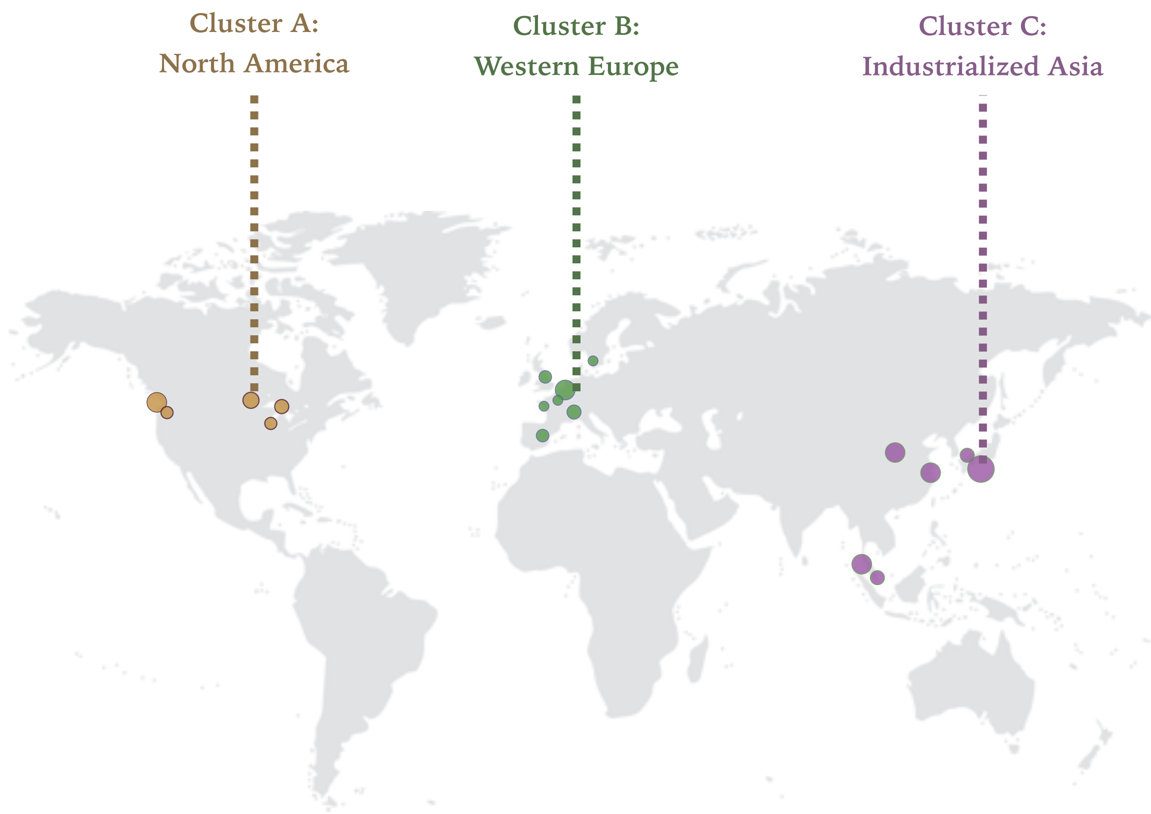
Source: 15A: Plantui official instagram page; 15B: Space 10 website [Online] Available at: https://space10.com/project/lokal/

In conclusions, both high-tech greenhouses and indoor farming methods can be integrated in buildings. One system does not exclude the other, and new multifunctional buildings may integrate both systems to achieve high food production standards, considering that the two systems can grow different and complementary crops.

2. Choosing the geographical and climatical context

Most of the literature regarding Urban Farming projects states that their application and design greatly depends on the context in which they are developed. When analyzing the case studies, it was noted that most of the high-tech systems used for building-integrated agriculture took place in industrialized Asia, Europe, and North America (Fig. 16). This can be explained as the knowledge needed to operate such systems, the required technology, and the high initial investment costs might be a limit in developing countries, where the objectives of Urban Farming differ from the ones in the industrialized world. Hence, the relevance of Urban Farming projects for community food security varies geographically. For instance, the very rapid urbanization in many low-income countries calls for actions to address food security issues, which differ from the purposes of urban food movements seen in developed countries, which aims to foster cities' smart ways of living [47].

Fig. 16: The three macro geographical area where BIA projects were found in the analysis of the case studies



Source: *Own Work*

In this regard, in developing countries growing and/or acquiring food that has been produced locally is seen as an opportunity to survive in the city [2]. On the other hand, in the northern hemisphere, there is also a growing interest in improving urban food production, though from different perspectives than in the south [2]. Even though urban agriculture cannot supply any city with all of its food needs, in developing countries it can contribute to alleviating hunger in certain neighborhoods [48], while it can implement access to food in food desert areas in developed countries. That said, the aims of ZFarming projects in the urban food supply are different between developed and developing countries [2]. In developing countries, small-scale subsistence rooftop gardening plays an important role in feeding families or small communities reducing the pressure on families in food expenses. In developed countries, other than the issue of food security that is especially relevant for low-income neighborhoods that lack retail facilities offering fresh and healthy food, building-integrated agriculture experiences aim to implement overall sustainability of the urban eco-system [49], create design strategies linked to new food experiences [50], and to foster social inclusion in a multicultural society [51].

With this in mind, this research aims to investigate the possible impact of building-integrated agriculture on the urban environment in the developed world. Between the three macro-regions that were identified in the analysis of the case studies, this research operates in the European context, specifically in the Center-Northern European geographic area. The reasons standing behind the choice of this specific geo-climatic area are:

1. *Proximity to the physical places where the research was led*: as all the research process has been conducted in Europe, between Florence, Bologna, and Wageningen, during the analysis process of the case studies it was possible to find more accurate documents about the selected European projects. The possibility to retrieve more updated data, visit

the project sites and communicate directly with local governments and municipalities was the first reason why it was chosen to operate in the European context.

2. *Technological advancement and overall acceptance of soil-less agriculture*: As reported in the literature [1,2,7] and in this research, the development of Building-integrated agriculture practices highly relies on high-tech technologies to increase yields on relatively small spaces in urban settlements. Due to the specific characteristics of Northern Climates, high-tech greenhouses developed faster, creating a more consolidated culture and acceptance of these systems. Indeed, unfavorable weather conditions (compared to Mediterranean climates) made high-tech greenhouses deeply rooted in the food culture of Central and Northern European countries, which can amortize the high investment costs thanks to a wider distribution compared to Mediterranean high-tech greenhouses, which struggle to compete for soil-based agriculture practices and low-tech greenhouses.

3. *Local Urban Agriculture food-policies connected to the circular planning of the city*: In recent years, the European Union has promoted several agriculture policies to shift towards a more sustainable production system. Nonetheless, up to date, there is no trace of a common Urban Agriculture policy, which is mostly subordinate to countries and local policymakers. In this context, cities like Amsterdam and London have recently updated their agro-legislation regarding urban farming projects and put the effort into boosting circular strategies in urban development.

2.1 Proximity to the physical places where the research was led

This research was financed by the Italian government in the framework of the national doctoral program. The institution in which the research is developed is the University of Florence, but due to the international interest in the topic and the cross-disciplinary aspects of Urban Farming, this research fell under the *Doctor Europeus* sub-program and saw the participation of the University of Bologna and Wageningen University and Research for the development of the agricultural parts.

A fundamental step of the research was the analysis of the case studies displayed in Chapter 2. During the analysis of the case studies, it was possible to visit several of the selected projects and talk with the people who worked there or even developed them. The visited projects were all located in Europe (Table 6), as it was impossible to reach some selected projects located in the US and Singapore due to the recent coronavirus crisis.

Table 6: Visited projects

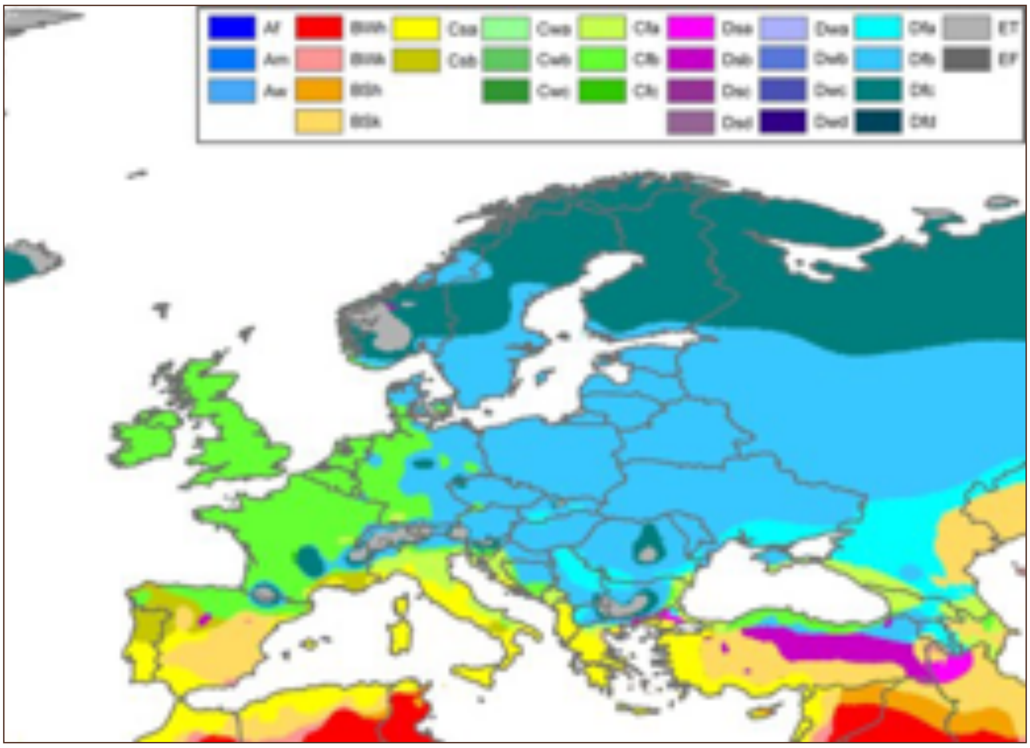
Code	Name	Location	Date
U01	Bajes Kwartier	Amsterdam, The Netherlands	April 2018
U02	ReGen Village (Only the location)	Almere, The Netherlands	March, 2019
B04	The Greenhouse Restaurant	Utrecht, The Netherlands	January, 2019
RG04	ICTA building	Barcelona, Spain	May, 2019
F01	Urban Algae Canopy	Milan, Italy	August, 2015 (during the EXPO 2015. Visit done for the Master Thesis)

Furthermore, the participation in many meetings and conferences between Italy, The Netherlands, and the UK has implemented the candidate knowledge of Urban Agriculture policies and actions in Europe. Thus, after a deep consultation with the tutors of this thesis, it was decided to develop the applicative part of this research in the European context, as it seemed more pertinent to the knowledge acquired during the construction of the framework of this thesis.

2.2 Technological advancement and overall acceptance of soil-less agriculture

A second step in the definition of the scenario of intervention consisted in determining the geographical area in Europe in which investigate the possible impact of building-integrated agriculture on the urban environment. Considering the aim of this research, which is studying the impact of all-year off-soil production in an urban environment integrated with architectural building, it was decided to operate in the specific Cfb climatic area (Temperate with no dry season and warm summer) [52] (Figg. 17-18). As written before, this climatic geographical area corresponds to the Center-Northern part of Western Europe (France, England, Ireland, Belgium, The Netherlands, Luxembourg, and Western Germany). This choice was made as the climatic characteristics that will be reported below, brought these countries, especially The Netherlands, to develop high-tech greenhouses in the past decades [56]. Thus, they have an already established market for the commercialization of off-soil production, and a better acceptance of this kind of product as it is deeply rooted in their food culture.

Fig. 17: Kottek climate configurations in the European Continent



Source: *Kottek at al. [52]*

The Kottek configuration

During this research, it was extensively described how different climates affect indoor crop cultivation, and how the design of hydroponic greenhouses may vary depending on the geographical and climatic area in which they operate. Greenhouse structures and equipment differ greatly around the EU depending on the climate conditions, the technologies, and the workforce available in the region [55]. Considering the Western European setting, where most of the case studies were found, it is possible to encounter two major climate zones in the Kottek configuration [52] (Fig 17): the Csa zone (Mediterranean climate) and Cfb zone (Marine West Coast climate).

The first quantitative classification of world climates was presented by the German scientist Wladimir Köppen (1846–1940) in 1900 [52] and later updates as a world map in 1954 and 1961 by Rudolf Geiger (1894–1981). Köppen climate classification used a vegetation-based, empirical classification system. The aim was to identify climatic boundaries so that they could correspond to those of the vegetation zones [53]. Köppen published his first scheme in 1900 and a revised version in 1918. He continued to revise his system of classification until he died in 1940.

The last update was provided by Kottek et al. in 2006, and it is based on Köppen's classification, which divided the planet into five major types, which are represented by the capital letters A, B, C, D, and E. The five letters represent five different vegetation groups, distinguished between plants of the:

(A) equatorial zone
(B) the arid zone
(C) the warm temperate zone
(D) the snow zone
(E) the polar zone.

The second letter in the classification considers the precipitation and the third letter the air temperature. Put together, the three letters of the Köppen's classification define a specific climatic and geographic area. The climatic characteristics of the chosen geographic context are then defined by the following table:

Table 7: Example of the use of 1st, 2nd and 3rd letter in the Köppen's climate configuration

1st letter	2nd letter	3rd letter	Criterion
C			Temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month less than 18 °C but greater than –3 °C. [53]
	s		Precipitation in driest month of summer half of the year is less than 30 mm and less than one-third of the wettest month of the winter half. [53]
	w		Precipitation in driest month of the winter half of the year less than one-tenth of the amount in the wettest month of the summer half
	f		Precipitation more evenly distributed throughout year; criteria for neither 's' nor 'w' satisfied. [53]
		a	Temperature of warmest month 22 °C or above. [53]
		b	Temperature of each of four warmest months 10 °C or above but warmest month less than 22 °C. [53]
		c	Temperature of one to three months 10 °C or above but warmest month less than 22 °C. [53]

The Csa climatic area (Mediterranean climates)

Mediterranean climate (Csa and Csb in the Koippen's configuration) is characterized by hot, dry summers and cool, wet winters.

Location: Mediterranean climates are located between about 30° and 45° latitude north and south of the Equator and on the western sides of the European Continent [57].

Precipitation: The subtropical anticyclone brings subsiding air to the region in summer, with clear skies and high temperatures. When the anticyclone moves Equator-ward in winter, it is replaced by traveling, frontal cyclones with their attendant precipitation [57]. Mediterranean climates tend to be drier than humid subtropical ones, with precipitation totals ranging from 35 to 90 cm.

Temperature: Annual temperature ranges are smaller than those found in Marine west coast climates (Cfb & Cfc) [57] and is characterized by warmest summers and mild winters.

The Cfb climatic area (Marine west coast climate)

The **Cfb** (together with the Cfc) climatic area, also known as *"Marine west coast climate",* are equable to climates with few extremes of temperature and ample precipitation in all months.

Location: It is located poleward of the Mediterranean climate region, on the western sides of the European continent, between 35° and 60° N and S latitude [54]. In Europe the major mountain chains (the Alps and Pyrenees) run east–west, permitting Cfb climates to extend inland some 2,000 km into eastern Germany and Poland.

Precipitation: Are variable somewhat throughout the year in response to the changing location and intensity of these storm systems, but annual accumulations generally range from 50 to 250 cm, with local totals exceeding 500 cm where onshore winds encounter mountain ranges. Not only is precipitation plentiful but it is also reliable and frequent. Many areas have rainfall more than 150 days per year, although the precipitation is often of low intensity. Fog is common in autumn and winter, but thunderstorms are infrequent. Strong gales with high winds may be encountered in winter [54].

Temperature: Mean annual temperatures are usually 7–13 °C in lowland areas, the winters are mild, and the summers are relatively moderate, rarely having monthly temperatures above 20 °C.

Differences in Greenhouse design and approach in Marine west coast climates and Mediterranean climates

The two main climatic areas that characterize Western Europe led to the development of two distinct production concepts. The majority of greenhouses in the Mediterranean area are low cost, low-tech, and labor intensive, while in Central and North Europe, greenhouses are mainly high-tech and demand a higher investment cost per square meter, tending to cover larger areas and require less labor [55]. This can be explained as Mediterranean horticulture benefits from the availability of abundant autumn and winter light and the mild winter conditions resulting from the proximity of the growing areas to the sea [56]. Montero et al. [57] made a distinction in these two methods:

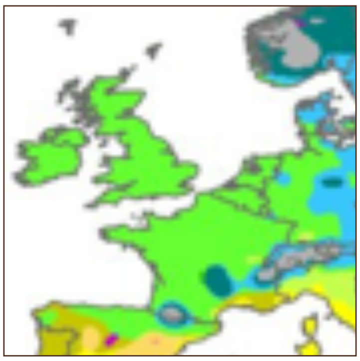


Fig 18: Cfb climatic area
Source: *Kottek et al. [52]*

•Cold countries adopted advanced greenhouse technology, increased light transmission, saved energy for heating and optimized all production means to achieve maximum yield; they used glass as covering material.

• Southern or Mediterranean greenhouses adapted to the local conditions, with moderate investments and little (if any) climate control system besides natural ventilation; this produced suboptimal conditions for plant production and as a consequence lower yields than high-tech greenhouses; they used mostly plastic film as covering material.

High-tech greenhouses in Cfb climates are capable of providing the optimal conditions for year-round production, but they are the most expensive option in terms of capital, running costs and energy consumption [56]. On the other hand, low-tech greenhouses diminish the risk of variations among price paths in different years, having less to lose when crops prices go down. unlike their Dutch counterparts with expensive modern greenhouses. That shows how best practices and techniques in one location (e.g. Dutch high-tech greenhouses) are not necessarily profitable in other locations (South Spain or Portugal). In this sense, the most profitable infrastructure for a specific region is not necessarily the most expensive and high profits can also be achieved using intermediate-level greenhouses or low cost structures [56].

2.3 Local Urban Agriculture food-policies connected to the circular planning of the city: the cases of London and Amsterdam

The European farming system is called upon an unprecedented challenge: changing the direction of national agricultural practices, transitioning towards more sustainable initiatives. As of today, the environmental impact of agriculture in Europe is catastrophic. Europe loses 970 million tonnes of soil every year, with more than 11% of the EU's territory affected by moderate to high soil erosion [58]. The use of herbicides, pesticides, and nitrogen-based fertilizers is dramatically reducing biodiversity in the European continent, threatening future yields [59]. Despite the great pressure European agriculture has on its soils and ecosystem, 31% of the land required to satisfy European food demand is located outside the continent [60], importing around 22 million tons of soy-based animal feed every year [61]. EU imports consist of one-quarter of global trade in soy, beef, leather, and palm oil, which caused illegal deforestation phenomena in the tropics [62], resulting in mass migration to urban areas in the developing regions of the world. Thus, the EU food system is enlarging its environmental footprint not only in its territory but all over the world. Furthermore, there is a disproportion between the actual food-demand of EU citizens and the overall impact of the EU food-system, considering that 20% of the food produced in the EU is lost or wasted [63].

In this scenario, the need to adopt a new, integrated governance approach for food systems has been increasingly recognized across EU institutions and policy circles [63]. Over the years the EU has started several studies to launch a comprehensive food policy calling for new solutions for the transitioning of the European food system towards sustainable and organic practices [63]. Nonetheless, there is still a huge gap between policies developed at the national and EU level, and those social, citizens-led innovations. In the preface of the report 'Towards a common food policy for the European Union' [63], Olivier de Shutter wrote that EU top-down policies tend to homogenize, rather than encourage local experimentation. Thus, it is important that the EU would support diversity rather than uniformity, encouraging networks of local actors, protecting fairer and region-based food-systems. In other words, there is not a common EU policy that managed to reconcile the multiple aspects of sustainability - economic, social, and environmental. Most policies, such as the Common Agricultural Policy (CAP), have relied on reinforcing a highly specialized, industrialized, standardized, and export-oriented model of agriculture and food production [63]. In this context, Urban Agriculture practices are left outside of a comprehensive EU food policy and completely relate to regional or municipal actions. Hence, cities and regions are emerging as major actors in food innovations and might be the lead promoters of urban farming projects, in lack of EU indications. The same Phil Hogan, commissioner of the EU Agriculture and Rural Development program, admitted that none of the available measures within the rural development programs 2014-2020 targeted towards the promotion of urban agriculture

[64]. Thus, it is up to the Member States to choose the types of UF operations or measures they want to include in their rural development programs.

In this complicated scenario, where the European Union struggles to promote clear policies that foster sustainable agriculture and circular horticulture, and where most of the actions are left to municipalities, regions, and nations, this research aims to assess the impact of UF in those contexts where strong circular farming policies are already developed and put into the political agenda. Within the chosen climatic and geographical area, this thesis examined the approach of two major cities in two great countries in Western Europe: the UK and The Netherlands.

2.3.1 UK: The London Food Strategy

The London Food Strategy has been developed by the Greater London Authority (GLA) on behalf of the Mayor of London and in partnership with the London Food Board. The London Food Strategy aims to ensure all Londoners have access to healthy and sustainable food [65]. The reasons standing behind the decision of the Mayor of London to implement a local food strategy lie in the high impact the food system has on its citizens and the environment. As a metropolis, London is the emblem of the contradictions in the modern food system: here, one-third of the whole food supply that enters the city is lost, meaning that for every two tons of eaten food, one ton is wasted [66]; food and drinks reaching Londoner's table account for 10% of London total consumption-based GHG emissions. This causes a significant impact on England’s soils, biodiversity, and water quality. Worsening the situation is London’s population prospect, which is projected to increase by 70,000 every year, reaching 10.8 million in 2041 [67]; even though London local food economy is worth around 20 billion a year [65], the city imports 31% of its food supply from the EU [68].

Nonetheless, urban agriculture is a thriving new economy in London, with more than 2700 new growing spaces being set up in the city and with over 200 thousand Londoners involved in food production [65], which makes London one of the most vibrant urban food growing networks in the world. Growing spaces cover more than 79 hectares and are an important part of London’s green infrastructure [65]. They are located in schools, housing estates, and parks, and on the urban and peri-urban fringe. In this context, it does not come as a surprise that the Mayor of London inserted Urban Farming as a fundamental principle of the new food strategy with the aim of “promoting the multiple benefits of food growing for individuals and communities” [69].

In the London Food Strategy report, the local government acknowledged the environmental economic, and social benefits of Urban Farming projects. They are seen as a way to (i) improve London’s green infrastructure and providing diverse habitat for London’s biodiversity; (ii) create social enterprises, boost local economies, and provide jobs, training, and apprenticeships, as well new opportunities which can help Londoners develop skills and lead to employment; (iii) bring communities together, help people feel less isolated, make areas safer, and improve people’s physical and mental health and wellbeing [65]. For these reasons, the municipality believes that it is important to incorporate space for food growing into new development plans, concluding that by working with local authorities, private sector partners, and food growing charities, the Mayor will support urban farming, encourage community growing spaces and protect allotments.

In this regard, some key strategies concerning ZFarming and Building-integrated agriculture are also taken into consideration in the London Food Strategy. The municipality intends to support these kinds of projects through the implementation of few strategic key points [65]:

- Use the new London Plan (still in its draft version) to highlight the importance of including food growing spaces in new developments and urban planning.

- Through the new London Plan, encourage innovative ways to deliver small-scale food growing, such as green roofs and walls, using vacant or under-used spaces, and incorporating spaces for food growing in community settings.
- Work with initiatives that develop training programs to support people to set up food-growing enterprises, invest in the emerging nature-friendly farming sector, to help London become a leader in green circular economy jobs.

The analysis of the London Food Strategy gives important feedback on what was written and studied in the first part of this research. That is that transitioning towards sustainable and environmentally-respectful food systems needs accurate and diffuse planning, and it cannot be reached with singular initiatives only. Furthermore, the benefits that urban farming projects can have on the urban environment cannot be exploited without connecting all spheres of sustainability within the city planning. In this sense, circular planning strategies are key to connect urban infrastructures and architecture with new sustainable food systems. The London Food Strategy seems to acknowledge that new off-soils food systems are a full-fledged new paradigm for urban planning, recognizing that "there are great opportunities to embrace emerging technologies. Food is a key part of London's emerging low-carbon circular economy, and through procurement, consumption, food growing, and innovation London has the potential to improve its food system" [70].

Furthermore, shifting towards circular food strategies that are integrated within the urban tissue could generate an additional £2-4bn GDP per year by 2036 [71]. In this regard, Urban Farming and food production, have been used as one of the six key strategies for the development of a new London circular economy to reduce food wastes by at least 20% [71]. Transitioning towards a circular food economy means supporting more resource-efficient and regenerative agricultural practices like precision and organic farming, the use of all by-products and waste streams along the whole food supply chain, extending urban farming practices [71]. Connecting circular food strategy with the built environment, promoting sustainable design principles such as modular construction, the use of building materials within high value closed loops for efficient disassembly techniques [71], and encourage buildings' repurposing can "capture and leverage the full value of activities such as land restoration programs, adoption of design principles (e.g. energy-neutral buildings), new materials as well as integrating supporting information and communication technologies" [72]. For London, adopting circular economy principles within the built environment means new opportunities across interconnected areas of urban living [71].

2.3.2 The NL: Amsterdam Circular Plan strategy

The Netherlands is a small, yet highly densely populated country, where about 70% of the people live in urban areas. Nonetheless, it is the second world food exporter, second only to the US which has 270 times its landmass [73]. The huge amount of food produced and exported by The Netherlands is the result of years of experimentation on climate control, artificially illuminated, high-precision farming greenhouses. The advancement in the food technologies required to operate these greenhouses made the Dutch agricultural sector famous for its productivity and efficiency, making the country one of the most food-secure nations in the world. Thus, differently from the UK, the Netherlands exports more than what they import, counting on a solid food-supply base and an already up and running advanced food-system. Nonetheless, the Dutch Ministry of Agriculture has worked on a new policy to promote circular agriculture [74], intending to connect food to other themes such as energy, water, transport, and health care. In this regard, the Dutch government has started to co-operate with the other EU Member States to get financial, legislative, and technological incentives that promote circular agriculture [74]. In this sense, The Netherlands brought food policy onto the agenda of the EU Agriculture Council and held national consultations on developing a comprehensive food policy, based on recommendations from a government-commissioned report by the Netherlands Scientific Council for Government Policy [63] that is supportive of the transition to circular farming.

On a national level, a document developed by Wageningen UR on re-rooting the Dutch food system from more to better [75], envisions the goals of a future circular agriculture policy in which Dutch citizens by 2050 will consume about two-thirds of their proteins from plants and one third from animal-based foods. In this scenario, the increased production and consumption of plant-based foods will result in more by-products such as crop residues, co-products from industrial food processing, food losses and waste, and human excreta that need to be reused. In this vision, urban areas will still depend on their hinterland for food supplies, hence, most of the by-products produced in the city should go back into the land in form of fertilizer creating a regional cycle of nutrients. Nonetheless, farming in and around densely populated urban areas also has essential social and environmental benefits, increasing consumer awareness and education about food production, promoting the connection between consumers, producers, and nature [75].

In this context, Dutch cities will become the hotspots of nutrient cycling. Nutrients are imported through food and exported through human excreta as unavoidable food waste. As for today, most of the phosphorus and nitrogen in the current food system is lost through human excreta, while recycling it would mean cutting our ties with the extraction of finite phosphate rock, which excavations have become unsustainable. Addressing the nutrient cycle is, in fact, a top priority of the Dutch Ministry of Agriculture's new policy, and the Government is intending to work with industry and science to promote more use of residual flows from food production and consumption, both in feed and as a fertilizer, and support entrepreneurs, with a role for the national Circular Economy Accelerator [74].

In this context, the Amsterdam municipality sets the objective of becoming a fully circular city by 2050 and acknowledged that a systemic change is needed to achieve this ambition. The city of Amsterdam is the first city in the world to use the Doughnut economics model (Fig. 19), which allowed city planners to model an integral circular economy strategy for the period 2020- 2025; at the core of the Doughnut, there are environmental, societal, and economic considerations. In this scenario, the City decided to prioritize the value chains of three key sectors, as stated in the report "Building blocks for the new strategy AMSTERDAM CIRCULAR 2020-2025" [76]:

- Construction
- Biomass and Food
- Consumer goods
-

The importance of intervening in these sectors can easily be explained by looking at the current situation where the construction sector creates 40% of total municipal waste; consumer goods represent the largest environmental impact of households; and one-third of all food goes to waste [76]. By reaching new circular models in these three value chains, Amsterdam hopes to contribute to substantially decrease their associated environmental impacts. Furthermore, the new circular strategies may present an opportunity for the creation of added value and jobs in the local economy [76].

In this regard, it does not come as a surprise that in the Amsterdam Circular 2020-2025 [77] an entire chapter is dedicated to the Food & Organic Waste stream relating to Urban Agriculture and ZFarming projects. The aim of the municipality is to shortening the food supply chain, bringing food closer to Amsterdam citizens, closing the nutrients loop on the local scale. As stated in the previously cited document written by the *Gemeente Amsterdam* (Municipality of Amsterdam), Urban Agriculture must have its place in the city, helping to define its green contours. As underlined in this report, a key point for the success of UA is that it should not come in conflict with the expected densification of the city itself, and that can be achieved by using ZFarming principles, cultivating in and on buildings, not occupying valuable building land.

Fig 19: Amsterdam Doughnut economics model

Source: *City of Amsterdam (2020), Amsterdam Circular 2020-2025 Strategy. Edited by Circle Economy and the City of Amsterdam [77].*

The role of Urban Agriculture should be mainly focused on its social function rather than contributing to increase an already strong food-security, creating awareness, participation, and connection in the local population. It is possible to identify three main objectives related to the implementation of Urban Farming projects in the Gemeente Circular Plan:

i) *Fight Climate Change:* Urban agriculture, and circular agriculture mitigate the effects of chemical fertilizer on climate change, by dramatically reducing or even removing it in soil-less agriculture. Less fertilizer requires less energy to produce or transport it, and prevents exhaustion elsewhere. Shortening the food chain can reduce $CO2$ emissions, and in this sense the City is planning sustainable logistics in cooperation with the City Distribution Project Office, to implement the diffusion of local produced food within the city of Amsterdam.

ii) *Prevent Nitrogen and Phosphorus saturation:* Closing local nutrient cycles requires the City to play an active role, for example by connecting all parties so that knowledge is developed and shared, and to match regional supply and demand. Transitioning towards circular, urban agriculture is seen as one possible way to make a positive contribution to the recovery of nutrients in urban areas.

iii) *Foster Education:* Urban agriculture can teach Amsterdam's residents about food production and inspire them to grow their own food. This can contribute to raise awareness of food consumption, greater appreciation for food, and eventually reduce food waste. Collaboration with knowledge institutions and secondary and higher education institutions is considered an important step. Thus, financing researches into product development, dietary change, behavioral change, and the development of innovations in food is top priority of the Amsterdam City Council.

Connected to the achievement of implementing city and regional-based food consumption within citizens, the municipality has prepared a plan of action for the five-years time 2020-2025, which main strategies have been reported below:

i) *Find a place in the city for food production.* Instruments: *spatial planning, collaboration platforms and infrastructure.* Urban agriculture in the city will focus on the social function: awareness, education, participation, connection. The City wants to actively support the participation of Amsterdam residents, knowledge institutes and businesses in the sustainable metropolitan and regional production of food.

ii) *The City purchases regionally produced food*. Instrument: *direct financial support*. The City is willing to stimulate the use of regionally produced products and food with direct financial support to those initiatives who promote locally grown produce.

iii) *Promote the collaboration between different sustainable parties in order to increase the consumption of regional food*. Instruments: *collaboration platforms and infrastructure*. The City is opening to all chain parties (producers, distributors, processors, sellers and food preparers) to jointly draw up a plan of action to promote the consumption of regionally produced food. Monitoring and information provision are an integral part of this, as are finding or developing markets (e.g. in schools, hospitals and other social institutions) and business models to fund the potential additional cost of regionally sustainable food.

Furthermore, the importance of Urban Farming in the Amsterdam Circular Plan resides in the fact that the municipality will initiate the transition from consumption of animal-based proteins to the consumption of vegetable proteins before 2023 [77]. In this scenario, farming within the city borders is considered a powerful tool to i) educate people on vegetable-based diets, and ii) implement access to fresh fruit and vegetables in the city, bringing closer producers and consumers. Moreover, the Municipality of Amsterdam believes that reducing the consumption of animal-based proteins, together with the implementation of a local food strategy (the *Amsterdamse Voedselstrategie,* which is still in its development phase) may contribute to dramatically reduce food waste, which now amounts to 41 kg/year per person of edible products thrown away [76]. Shifting towards plant-based diets and the reduction of food waste has the objective of:

i) *Promoting educational programs:* Education plays an important role in the ambition to change Dutch food pattern. On the one hand, the importance of balanced, sustainable nutrition must be included in teaching materials. On the other hand, it is important to develop and share innovation in production techniques, business models and organizational forms for circular food production.

ii) *Encouraging land conversion:* Tackling food waste and promoting a plant-based diet can be achieved by a more efficient use of agricultural land. Thus, contributing to the reduction of greenhouse gases, soil degradation, biodiversity loss and nutrient surpluses (and shortages).

iii) *Improving citizen's health:* Projects that stimulate sustainable food consumption can improve the health of Amsterdam's residents. In addition, initiatives that reduce food waste can also have a social component. For instance, the creation of food banks that promote no-waste dinners could bring residents together in a multicultural city.

iv) *Fighting climate change:* Less food wastage and a reduction in the consumption of animal products may lead to less direct emissions of greenhouse gases and nitrogen. The Municipality also hopes to decrease indirect emissions as less food-transport is needed. Soil subsidence connected to livestock farming also is expected to decrease.

The way the City intends to achieve these objectives is summarized in three key points:

i) *Encouraging the people of Amsterdam to change their eating habits.* Instruments: *knowledge, advice and awareness*. The City and its partners are working together to encourage Amsterdam's residents to eat healthier and more sustainably through awareness-raising campaigns and the Amsterdam Approach to Healthy Weight (*Amsterdamse Aanpak Gezond Gewicht*). In this context, the Municipality is also willing to change the policy for advertisements in public spaces so that more attention is paid to healthy, sustainable food and less attention to unhealthy food with a large ecological impact.

ii) *Municipal commitment to reducing food waste*. Instruments: *regulation, economic frameworks, knowledge, advice and awareness*. The Municipality is willing to combat food waste with policies aimed at specific sectors and at specific groups of Amsterdam residents. Using, for instance, awareness-raising and economic instruments to discourage food waste and ensure that surpluses find their way to those residents who need them most.

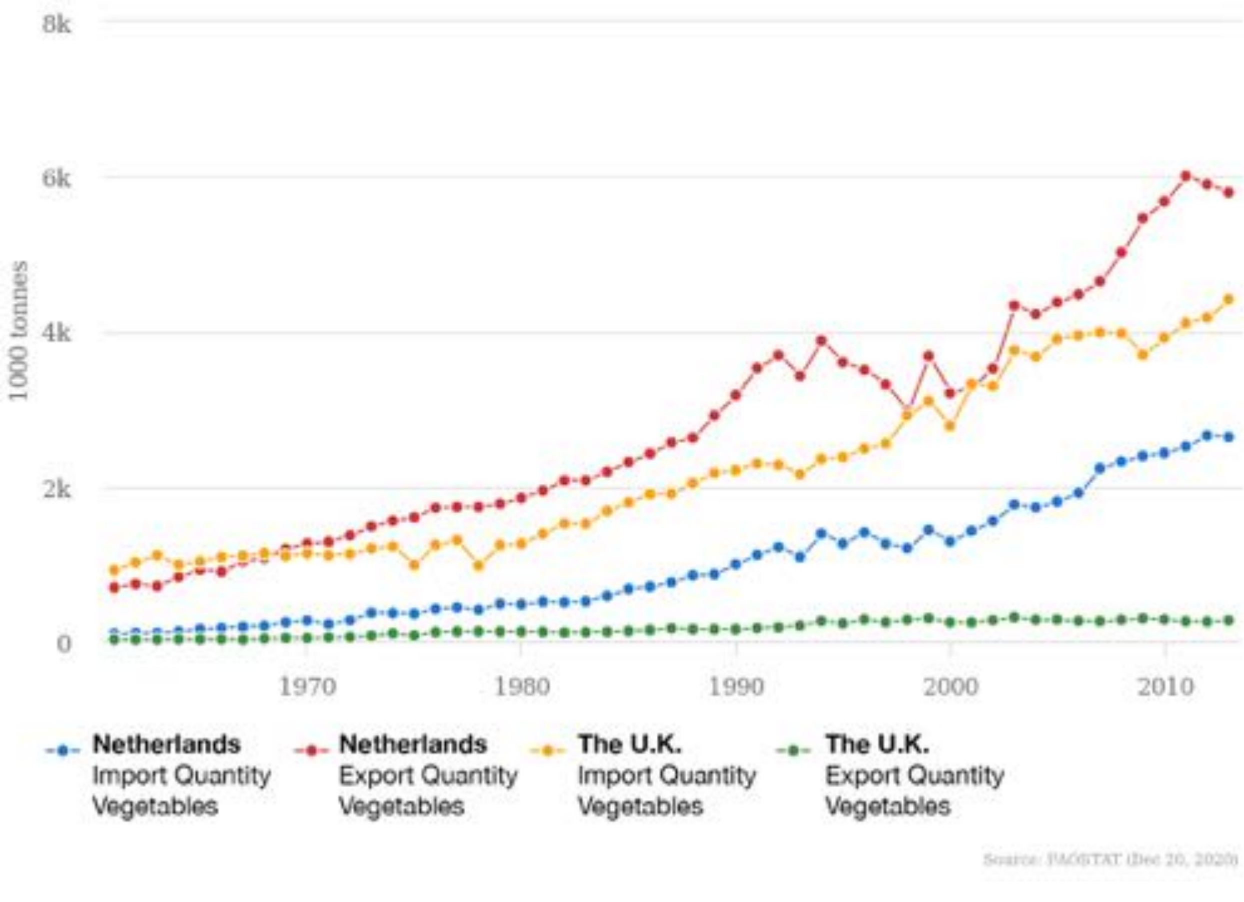
iii) *Municipal support to initiatives against food waste which are focused on more efficient production of food.* Instruments: *fiscal frameworks, direct financial support, knowledge, advice and awareness, collaboration platforms and infrastructure*. The City wants to supports initiatives from all corners of society that fight against food waste and for a more sustainable, healthier diet – i.e. by offering solutions in logistics, data, value retention, accessibility or engagement and community involvement, but also in the field of food technology that can provide tasty sustainable alternatives.

In conclusion, similar to the The London Food Strategy, the Amsterdam Circular Plan confirms that, in lack of common EU policies, municipalities play an important role in diffusing and promoting Urban Farming projects. The Netherlands has a different food system in comparison to the UK, for this reason the core of the urban food strategy proposed by the municipality of Amsterdam differs in some key points in respect to the London food strategy. Nonetheless, both plans have a specific focus on implementing new circular food economies. In this sense, the Dutch government is particularly interested in closing the loop of nutrients in the future food production system. Thus, smart and advanced production technologies may favor the development of ZFarming projects in the city of Amsterdam and other Dutch municipalities. The strategic plan envisions that the municipality of Amsterdam will start before 2023 to improve the collection and processing of organic waste streams from Amsterdam's residents, visitors, businesses and institutions. At the state of the art organic waste streams in Amsterdam are divided into food waste and wastewater on the one hand and waste from gardens and public spaces on the other [77]. To process the first group into high quality products, an effective collection system is required that ensures that waste streams are not cross-contaminated [77]. For this reason, it is fundamental to improve a system of separate waste collection for both households and businesses. Effective separation at the source does not only generate more usable organic waste, but also improves the quality of other waste streams, such as household residual waste. As it will be extensively discussed in the next chapter, new technologies and policies and an engaged community can contribute to achieving this goal [76]. Once separated, the Municipality of Amsterdam is planning to reuse the waste streams in a wide range of useful products (e.g. fibers for building materials or even as chemical building blocks for plastics and coatings) [78]. Furthermore, by involving Amsterdam citizens together with the city's businesses and institutions in the collection and up-cycling of food waste, the Municipality hopes to improve the collection and processing of organic waste, that will permit the recovery and reuse of nutrients, thus reducing the need for artificial fertilizers in both land-based and off-soil new agriculture system.

2.3.3 Historical development of the Dutch and British food systems: how centuries of local agricultural policies are influencing contemporary food strategies. A comparison of the two systems

The London and Amsterdam food strategies are strongly influenced by the national government's agricultural policies, which, in turn, are connected to centuries of agricultural development. The evolutive analysis of the agricultural processes that occurred in the UK and The Netherlands can be a useful tool to understand the slight differences that were encountered in the British and Dutch contemporary food strategies. As of today, The Netherlands is one of the biggest producers and exporter of food all over the world, which can be surprising considering the small extension of its land, and the harsh conditions of its soils. On the other hand, differently from The Netherlands, the UK imports most of its food from abroad, and in great part from the EU union (31% of the whole UK supply) [80]. This is because the national agricultural system is substantially not structured to provide for its population. For instance, when looking at the chart shown in (Fig. 20), it is possible to see how vegetable exportation in the UK is approximately zero, while it seems that most vegetables are imported.

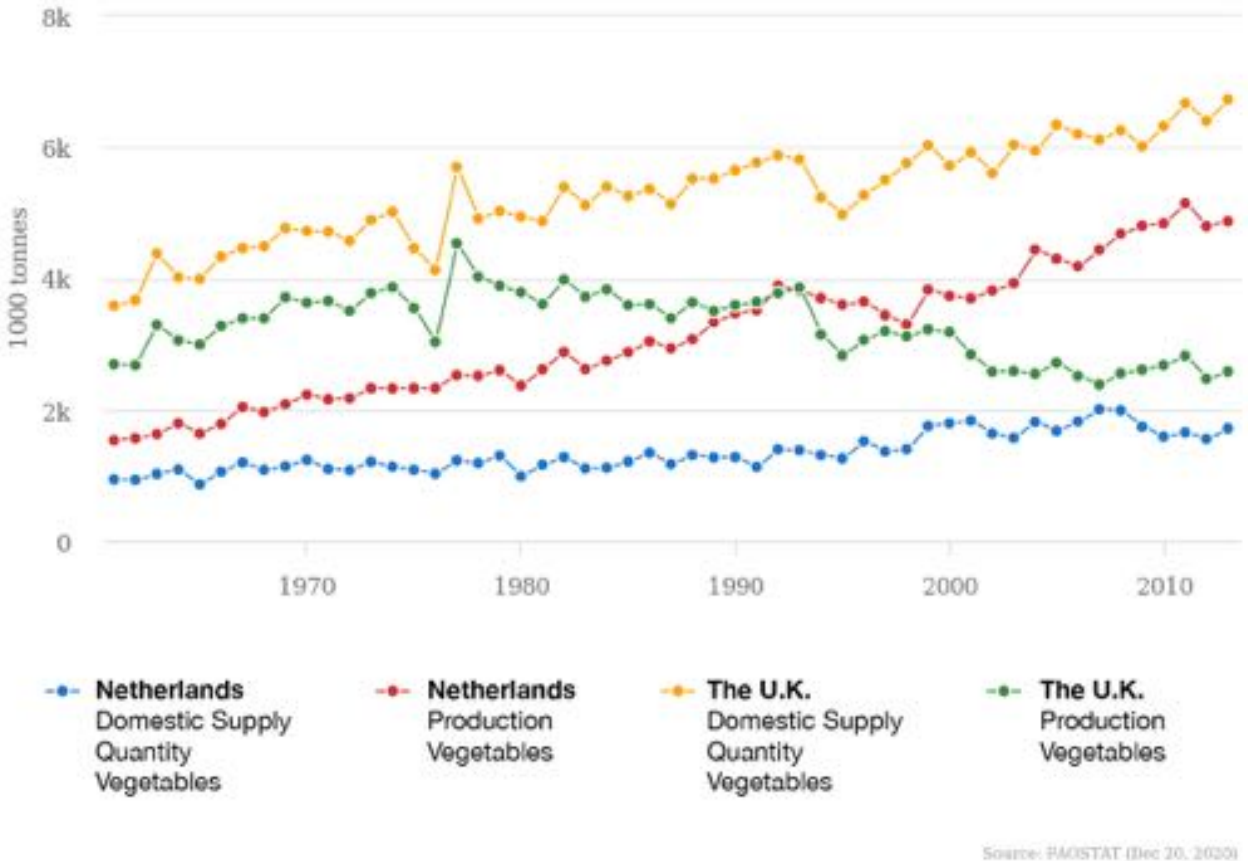
Fig 20: UK and The NL vegetables import and export quantity. A comparison



Source: *FAOSTAT. Accessed December 2020*

Comparing the import and export data shown in the first chart to the production and domestic supply quantity of vegetables of the two countries (Fig 21), it becomes clear that the UK is producing much less than what it needs to feed its population. Especially when looking at a new food approach, like the one proposed by the London Food Strategy, that pushes towards a reduction in the consumption of meat and dairy products, the UK may be extremely subjected to fluctuation in the vegetable market trades. On the other hand, The Netherlands produces twice as much as it needs to feed its population. Hence, it is not surprising that the quantity of vegetables exported is almost three times that imported.

Fig 21: UK and The NL vegetables production and domestic supply quantity. A comparison



Source: *FAOSTAT. Accessed December 2020*

The deep differences in vegetables and food production that can be appreciated in the charts can be explained by the different evolution of the two farming systems and the complex policy infrastructure promoted by the two governments throughout the years. For instance, already by the end of the 19th century, the UK was the world's biggest importer not only of grain, but of processed and preserved foods as well [81], importing wheat from the American midland, exotic fruits from California, milk from Switzerland, and even frozen meat from Australia. That would seem strange in a country where 70% of habitable land consists of farmland [81].

Nonetheless, the agricultural policies that were carried on in the past century exacerbated the gap between production and local food demand. The agricultural system that was used for centuries was hit hard when the German ships cut off the Atlantic supply chain, causing one of the worst food shortages of the UK's history, showing the total inadequacies of the British food system. In 1947, in the name of increased productivity, the British government released the Agricultural Act, which allowed farmers to spray DDT and use chemical fertilizers on their fields. The result was that in the 50 years after the war, "Britain lost an estimated 190,000 miles of hedgerow, 97 percent of its flower meadows and 60 percent of its ancient woodlands" [81]. As of today, after years of intensive farming, the British countryside doesn't have much to offer in terms of biodiversity and productivity. In this context, from 2005 the British government divided farming subsidies from food production, which resulted in the fact that farmers instead of being paid to grow food, they would be paid to prettify the countryside and encourage wildlife [81]. This way, the British countryside has been transformed into a sort of “heritage theme park" [81], forcing the institutions to buy most of the food from abroad. In this scenario, a megalopolis like London may be at risk of food insecurity due to any possible hiccup in the supply chain. The recent Brexit situation, together with the coronavirus pandemic showed how delicate the balance of a food system that mostly relies on importation is. In a report written by T. Lang et al [81], the authors warned how “just-in-time” delivery systems are easy to be disrupted. The conjunction of the Coronavirus pandemic with the Brexit situation provided the world with a very powerful image of hundreds of trucks waiting in line to enter the UK borders. One day of blockage led to abrupt falls in the stock exchange and pound to euro exchange rates. In this context, the Brexit negotiations could threaten both supply chains and secure access to food, the London Food strategy sees Urban Farming as a concrete option to cope with possible system failures, in face of an inadequate food system that cannot possibly provide for its inhabitants. For this reasons, the new policies that are carried on by the Mayor of London primarily aim at reducing food insecurity in the greater London area, the most populated area of the country, and secondly at improving dietary habits of Londoners, having better control of the food that is produced and consumed in the capital.

On the other hand, The Netherlands has considered one of the most food-secure countries in the world thanks to a well-established food-system and centuries of battles against the harsh geological conditions the country lives in [75]. The lack of agricultural land had forced the Dutch to start importing grain and wheat earlier than many other countries. In doing so, by the sixteenth century, they already had an important and recognized merchant fleet with a strong presence in Danzig, where most of the European grain fields were located. By the mid 17th century, already more than half of the Dutch population lived in towns, and the land, much of which had been reclaimed from the sea, [81] was under a lot of pressure to feed all this urban population. Dutch farms were mostly small, sandy plots “made fertile by deep digging, constant weeding and plenty of fertilizer” [81]. In a pre-industrialized era, the Dutch farmers used ante-litteram circular-economy principles to bring fertilizers from the towns in the form of wood ash and manure: country and city were connected by a network of canals, that was used to carry the waste from the towns to the farms and, at the same time, bring back food in the opposite direction [81].

Furthermore, accurate farming practices like the use of fodder crops, allowed Dutch farmers to improve the quality of the soil and to provide winter feed for livestock, which were then slaughtered in Autumn. At the end of the 19th century, the whole farming system was modernized with the use of chemical fertilizers which dramatically increased agricultural production. Within a short period, the Netherlands became the largest consumer of artificial fertilizer per hectare of arable land [82]. In 25 years, the use of chemical fertilizers increased by 105 times in The Netherlands [82], creating an unprecedented economical boom in the farming markets which resulted in the increasingly growing number of agricultural cooperatives operating on the Dutch soil. After the war, the Dutch economy boomed, and the agricultural system kept growing at a pace of 4% average annual growth in productivity until 1980. The difference in this period in respect to the British system was the investment policy: due to the limited resources offered by the land, the Dutch government aimed at producing as many products as possible in a shorter period. To do so, the Ministry of Agriculture flowed a lot of new capital into the agricultural system for the development of technology and education. The total value of capital used in agriculture increased from 16 billion guilders in 1957 to 90 billion guilders in 1983, an annual growth rate of 7%. According to the FAO, the amount of fixed capital per hectare in The Netherlands in 1980 was 1,953 U.S. dollars, the highest in the world and 12.3 times that of the U.S [82]. Nonetheless, the intensification of production systems, which mostly focussed on increasing productivity, caused serious problems to the Dutch natural ecosystem: i) eutrophication of surface water due to nitrogen and especially phosphate emissions; ii) nitrate pollution of ground-water; iii) acidification due to the volatilization of ammonia originating from manure; iv) accumulation of heavy metals in soils and food [82].

The pollution of soil, water, and air caused by the use of chemical fertilizers pushed the Dutch government and farmers to transition towards new sustainable agriculture, investing in research and new technologies such as precision farming greenhouses and off-soil production techniques that still fees the Dutch population [73]. In this context, The Netherlands has a more advanced and diffuse agricultural system in respect of the UK. For this reason, the main goal of new governmental and local food policies is to improve the sustainability and circularity of the food system, connecting it to the always more diffused urban environment which covered most of the agricultural land of the last 50 years [75].

2.3.4 Objectives and strategies of London and Amsterdam food strategies. A comparison

As emerged form the analysis of several plans [69,70,71, 75,76,77,79] developed in recent years by the municipalities of London and Amsterdam, it is clear how new food strategies are directly connected to circular-economy principles. In both cities, food plans refer to new principles of circular agriculture and are embedded in the cities' spatial planning strategies. Nonetheless, the different evolution of the two food systems led to different aims and approaches in the proposed food strategies (Tab. **8.1** and **8.2**).

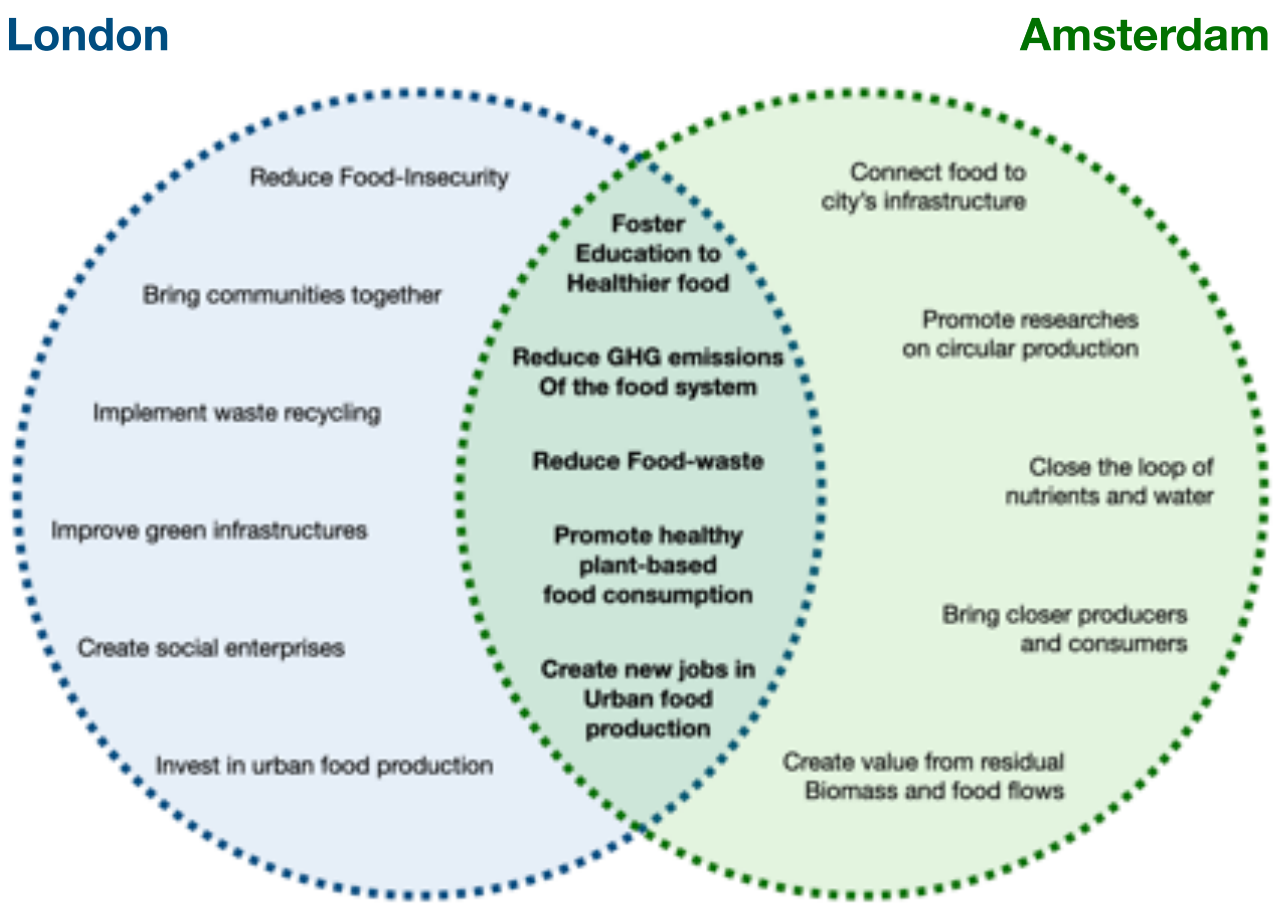
Tab. 8.1 OBJECTIVES

SPHERE	LONDON	AMSTERDAM
PRODUCTION & HEALTH	• Reduce food insecurity, ensuring all Londoners access to healthy food. • Reducing people's reliance on food-banks. • Fight increasing obesity in urban areas. • Encourage healthy, sustainable and plant-based food consumption by all citizens	• Encourage healthy, sustainable and plant-based food consumption by all citizens • Connect food to other themes such as energy, water, transport, and health care. • Implement access to fresh fruit and vegetables in the city, bringing closer producers and consumers.
SOCIAL	• Bring communities together, help people feel less isolated, make areas safer, and improve people's physical and mental health and wellbeing. • Foster education to healthier food and inspire people to enjoy good food together, as well as creating a more socially-integrated city.	• Promote food education, including the importance of balanced, sustainable nutrition in teaching programs. • Implement researches on technologies, business models and organizational forms for circular food production. • Creation of food banks that promote no-waste dinners that bring residents together in a multicultural city
ENVIRONMENTAL	• Improve London's green infrastructure and providing diverse habitat for London's biodiversity. • Reduce GHG emissions by changing eating and farming habits. • Reduce food wood waste. • Meet the 65 per cent overall municipal waste recycling target by 2030.	• Minimise food waste from retail, catering and households • Accelerate the closing of local nutrient cycles from biomass and water flows. • Reduce animal-based food consumption, limiting livestock's GHG emissions.
ECONOMIC	• Create social enterprises, boost local economies and provide jobs, training and apprenticeships	• Scale-up high-value transformation of residual biomass and food flows, providing new business opportunities, and new jobs.

For instance, urban farming in London can be an important input to fight food insecurity in the City, increasing local vegetables production that can help shifting towards future plant-based diets. On the other hand, the municipality of Amsterdam is willing to finance Urban Farming and ZFarming initiatives to connect food with other themes as energy, water, transport and waste. In this sense, the Municipality of Amsterdam sees Urban Farming projects as a way to close the nutrients loop in the city. Especially ZFarming projects can contribute to achieve this objective as i) they don't enter in competition with valuable building land, reducing initial investment costs; ii) they can recover waste directly from the buildings they are integrated with. On the other hand, London strategy focuses more on allotments and soil-based urban agriculture, seeing it as a possibility to implement city's green infrastructure and bring people and communities together. Here, ZFarming and building-integrated agriculture are seen as a way to boost urban circularity through the implementation of new technologies, connected to the entrepreneurial sector. Nonetheless, there are several shared objectives between the two plans, which implementation is crucial when transitioning towards circular food systems (Fig 22). These objectives are interconnected and are referred to the 4 dimensions of urban farming - social, economic, environmental and health.

The main objective of both plans can, in fact, be traced in the will of changing citizens' diets, aiming to shift towards the consumption of plant-based food in the foreseeable future. This objective is connected to the reduction of GHG emissions related to livestock production and food importation. However, shifting towards plant-based diets may result in an increased amount of by-products such as crop residues, co-products from industrial food processing, food losses and waste that in a circular economy of food must be reused. Hence, similar specific strategies to address this issue have been developed in both municipal plans, which involve encouraging local authorities to offer better waste recycling services, investing in researches and providing financial support to those businesses that engage in nutrient recovery, and using planning tools to design physical spaces where high-value reuse of biomass and by-products can take place.

Fig 22: A comparison of main London and Amsterdam food plans' objectives



Source: *Own work*

Both strategies, highlighted in Table **8.2**, aim to include urban farming within the urban planning process, thus, making food a full-fledge new paradigm for cities' spacial design. In this scenario, people will not only receive passively an imposed food system, but they could actively participate in the production process. Hence, both strategies aim to invest in education programs, starting from schools and public buildings, supplying education and training on organic and circular farming, inviting people to invest and buy locally-grown produce. In this sense, both municipalities are planning in limiting advertisement policies that promote unhealthy food and diets as a concrete action to start changing people's perception of food, financing local associations and entrepreneurs that grow food within the urban boundaries. Nonetheless, producing food in cities can be economically challenging, as required investment costs, especially for high-tech Zfarming projects, are very high. In this sense, what municipalities can do is to provide positive price incentives, such as subsidies, for startups to enable a scale-up, supporting and promoting values-driven food businesses and social enterprises, through the public awards and fundings.

Tab. 8.2 STRATEGIES

SPHERE	LONDON	AMSTERDAM
PRODUCTION & HEALTH	• Include food in the city planning, using green roofs and walls, vacant or under-used spaces for food growing in community settings.	• Include (peri-) & urban farming in spatial planning, and provide spaces for testing circular farming techniques.
SOCIAL	• Develop training programs to support people to set up food-growing enterprises, invest in the emerging nature-friendly urban farming sector that can create green circular economy jobs. • Change policy advertisement that promote unhealthy food and beverages.	• Supply education and training on organic and circular farming techniques and stimulate interest in Urban farming. • Educates citizens about circular and regenerative food production through school excursions and training of new urban farmers. • Change policy advertisement that promote unhealthy food and beverages.
ENVIRONMENTAL	• Encourage London public sector institutions to use more plant-based, seasonal, organic, and locally-sourced foods with minimal artificial inputs. • Support food outlets and retailers that consider the impacts of the food they sell and minimize food waste. • Encourage local authorities to offer better waste recycling services across London, including separate food waste collections. • Invest in new technologies to sell and consume sustainable-produced food.	• Provide municipal buildings with sustainable, plant-based food that is grown locally using regenerative practices • Use spatial planning to provide physical space and infrastructure for businesses and initiatives that close nutrient cycles and recover nutrients at a high-value. • Provide subsidies to create a positive cost/benefit ratio for products made from recovered nutrients • Provide financial support for businesses that engage in, and experiment with, nutrient recovery.
ECONOMIC	• Support businesses to scale up or adopt circular economy business models through the Advance London Programme and other investment programs. • Support and promote values-driven food businesses and social enterprises, through the Urban Food Awards and other funding support.	• Use spatial planning to design physical space where high-value reuse of biomass can take place, and create space for storage of biomass. • Provide positive price incentives, such as subsidies, for startups to enable a scale-up and develop innovations and realistic solutions.

In conclusion, both municipal urban food strategies aim at including Urban Farming in the spacial planning process, and are taking concrete actions to promote local food enterprises with specific focus on the circular aspects of production.

4. Conclusions: urban farming and circular horticulture as a boost for circular design implementation of European cities

As emerged from the London and Amsterdam food strategies, implementing new sustainable, environmental and people-friendly urban food systems means transitioning towards a circular food economy. When an urban food system goes circular it supports more resource-efficient and regenerative agricultural practices like precision and organic farming, and low and high tech protected cultivations. Here, the use of all by-products and waste streams along the whole food supply chain is recirculated and wastes and inputs collide, limiting the use and exhaustion of resources like soil, energy and fertilizer. Furthermore, in both plans, circular food strategies are connected with the built environment and the principles of circular construction, thus promoting sustainable design principles such as modular construction and the use of building materials within high value closed loops for efficient assembly/disassembly techniques [71, 77]. Hence, adopting circular urban horticulture within the built environment is seen ad an opportunity to connect different spheres of the urban living, implementing the sustainable growth of the modern metropolises. In this regard, both Amsterdam and London circular strategy plans [71,71,76,77] have shaped their vision of the city of the future in the connection of circular construction and circular horticulture, defining circular economy as "an economic system that replaces the 'end-of-life' concept with restoration" [55], shifting towards renewable energies, and eliminating waste.

Fig. 23: Circular processes in ZFarming

Source: *Own work*

In this context, circular horticulture is intended as a circular economy of food that consciously emulates natural systems of regeneration so that waste does not exist, but instead works as input for another cycle [78]. Today, thanks to soil-less protected cultivation techniques, it is possible to fully integrate greenhouses and plant factories in buildings, generating new synergistic relationships between the two entities (Fig. 23). The target in protected cultivation systems should always be to save resources and energy and to develop zero emission.
Nonetheless, the degree of circularity and sustainability depends on the quality of the inputs [55]. For instance, in hydroponic production, the quality and quantity of water flowing through the system is fundamental to determine and design the circular production system. In this scenario, recovering water from buildings may enhance the degree of circularity in the food-system. Recovery resources from buildings is, in fact, at the core of the Amsterdam circular strategies, whether this is done on site or in specifically designed infrastructures, such as digesters and water plants.

Buildings are, in fact, hot spots for nutrients and water recovery, fundamental resources to produce food in urban areas. Soilless cultivation systems and especially closed or re-circulating hydroponic systems can significantly reduce fertilizer runoff but not eliminate it [55], for this reason integrating them in buildings can benefit both entities developing water and nutrients closed-loops, eliminating dangerous runoffs. Nonetheless, even though high-tech greenhouses may present a high level of circularity, they need high investment cost, greater installation and running costs, and a high degree of automation and technical skill [55], which limit their applications in those areas in Europe where technologies and know-how are already known.

In this sense, municipalities play a crucial role in the development of ZFarming and building-integrated agriculture. Today, cities have the opportunity to spark a transformation towards a circular economy for food, given that most of all food is expected to be consumed in cities by 2050. Cities have the assets, the technology, and a dense networks of highly skilled workers that represent the ideal conditions for innovation in the food system. Citizens, retailers, and service providers are all in close proximity, making new types of business models possible where producers are directly connected with the consumers [78]. This combination of factors means that governments and municipalities have the means to implement a circular economy for food. This is why municipalities like Amsterdam and London that want to implement the design and use of Urban Farming and ZFarming projects have developed investment strategies in their plans, providing incentives and a distribution chain to those entrepreneurs that are willing to locally grow food. Connecting high tech production systems with the construction sectors, providing incentives also to developers and constructors, will foster a diffuse planning of ZFarming projects in cities, weakening the limitations represented by the initial investment costs and creating the business conditions for new urban food enterprises to thrive. Cities have, in fact, tremendous demand power as a great volume of food is eaten within them [78]. Furthermore, cities accumulate a large amount of food by-products and waste, that can be re-used directly in urban areas. In this context, new technologies and innovations in the food production sectors may be the key factors to minimize resource consumption while producing enough food to contribute in feeding growing urban communities. For this reason, the production systems that will be integrated in city planning must have nearly zero environmental impact [55]. This goal can be achieved by developing a sustainable indoor, off-soil production systems which [55]:

- does not need any fossil energy and minimizes the carbon footprint of equipment
- requires minimal amounts and does neither waste water nor causes emission of fertilizers and does fully recycle inputs such as water, nutrients and all growing media
- has minimal need for pesticides, yet with high productivity and resource use efficiency.

In circular protected horticulture plants grow in closed systems, where water and nutrients are recirculated and reused. These systems, like hydroponic or aquaponic greenhouses and indoor plant factories, require adequate management, and a deep knowledge of irrigation and fertigation techniques. For this reason, investment in research programs and in the education of the operators are crucial in urban areas to achieve high yields with maximum efficiency of the use of natural resources. When talking about building-integrated agriculture, the key elements to achieve a circular economy of food are the combination-clustering with buildings and the full control of inputs/outputs [55]. As reported in the first part of this chapter good practices for implementing circularity in protected indoor and off-soil cultivations when integrated in buildings can be summarized in the utilization of:

1. **Closed hydroponic systems.** Closed-loop hydroponic systems collect and re-use the superfluous exceeding nutrients, re-circulating them back into the system. The system can be applied to all sectors and geographical locations but it needs good quality water as an input [55]. However, the concept of closed or semi-closed hydroponic greenhouses is mainly applied in cold climates, where cooling is easier due to the cooler weather conditions. To apply the hydroponic system in practice, high expertise in water and nutrient management are essential.

2. **Aquaponics.** The Aquaponic system is a relatively new technology that combines recirculated aquaculture (the activity of breeding, raising and harvesting fishes) with hydroponic vegetable, flower, and herb production [17]. The advantages are a reduced need for water and fertilizer in crop production and also less need for water in fish production. The system can be applied to all regions/locations and is usually used for short cycle crops such as leafy vegetables.

3. **Integrated pest management (IPM).** 'Integrated pest management' emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms [55]. IPM can be applied to all crop types and locations but in general there is a lack of crop specific guidelines and require high expertise. IPM is especially recommended in high tech greenhouses where preventive measures for plant protection is enhanced by the characteristics of greenhouse construction.

4. **Adaptive cover materials and biodegradable mulching materials.** Adaptive cover materials that can be applied as additional layers to the glass cover affect mainly the solar radiation entering the greenhouse and also the energy losses by the greenhouse. Covering materials can be applied to all crop sectors (fruit, vegetables, ornamentals) and regions while mulching covers are designed for soil grown crops. Their use is limited by the high costs and in most cases their low durability in time.

5. **Metrics and Decision Support Systems (DSS).** Metrics, Models and DSSs are a common practice used in high-tech greenhouses. Here, sensors are used for assessing parameters related to climate, crop, soil/substrate and inputs and outputs in a greenhouse [55]. DSS are also characterized by a large quantity of data collected. DSS as a tool can be applied to all crop sectors and to all regions. However, the process of data and advice generation is not easy to understand. In addition, the experts consider that each crop may have different needs and that the systems are not adapted to each specific case. Growers need systems that would allow them to benchmark their performance and compare the results with the ones from other greenhouses.

Due to the hight technical requirements and expertise of high-tech protected agriculture, including urban farming in the planning process is crucial to the success of the development of circular horticulture in cities. That is because when these food systems are diffuse over a territory they are much more efficient than single initiatives. “Clustering” is, in fact, a strategy to implement the circularity of the cultivation systems. Furthermore, the development of holistic planning strategies that take into consideration both urban food production and architectural and spacial construction will help with the objective of reducing waste and GHG emissions by maximizing resource flows between urban entities. Clusters are made up of a set of companies, activities, services and products that, when incorporated into a given value chain (i.e. urban areas or urban districts), allow for greater efficiency in the production stages, through a better management of inputs and waste [55]. Clusters are made by different entities that concur to the production of food in urban areas, with the benefits of (i) exchanging “material” goods with eachother in a metabolic approach, and (ii) exchanging “immaterial” goods e.g. knowledge.

Clustering in cities means putting together food production systems with the built environment, offering a variety of economic advantages as well as environmental benefits such as the reduction of transportation costs and the recycling of production residues and waste. This may result in a significant increase of levels of circularity within a given clustered urban area. Some advantages of clustering are:

- Clusters are closely related to the value chain management, incorporating new processes, and practices that can diversify their business model.
- Clusters link agricultural production, processing, packaging, logistics, storage and trade with distribution chains to establish locally-based synergistic benefits.
- By clustering, SMEs can merge reaching a size that facilitates their access to knowledge, innovation, technical infrastructures and new markets, as well as their participation as consortiums in research and development and innovation projects with public or private partnerships.
- Clustering around cities and urban districts leads to savings in logistics and facilitates overcoming common administrative and legal barriers as well as high initial installation costs.
- Clusters in cities would increase resilience and reduce vulnerability of production systems by diversifying business and functions, incorporating Research, Development and Innovation resources and reducing their dependency on fossil and non-renewable sources.
- Clusters can drastically reduce environmental footprints, sharing inputs and outputs during the production process, adapting value chains to more sustainable systems.

The municipalities of London and Amsterdam in their food plan recognize the importance of clustering, and decided to include urban farming in the city’s spacial planning. They see Urban Farming as a key strategy for the transition towards a diverse and resilient food system, reconnecting people with food, and delivering a range of societal and environmental benefits [78], acknowledging that single, spot UF initiatives cannot contribute significantly to satisfy urban food demand and needs, especially in cities where population growth is constant. However, even when clustered indoor urban farming methods (i.e. vertical farms and hydroponics or aquaponics greenhouses) won’t be able to cover all the food needs within cities, and also when coupled with open-field Urban Agriculture, it is unlikely that they could provide for more than one third (by weight) of all the food needed for urban consumption [78]. Furthermore, planning strategies are effective only if they can overcome three main challenges of UF:

1. **Competition for land:** to be effective UF initiatives must be diffused over a territory. Finding farming spaces within the city can prove challenging due to zoning laws, technical feasibility and competition for other revenue-generating uses [78]. Of course ZFarming help avoiding the need of physical land, but it must face local regulations and the skepticism of local developers and farmers to invest in such projects. Single virtuous initiatives cannot be the answer to deeply routed problems in current urban food system, and the implementation of advanced building-integrated agriculture requires vision, planning and fundings both from the private and the public sectors.

2. **Limited crops type:** Crops that are typically produced in indoor greenhouses and vertical farms are sill limited to leafy greens, herbs, other vegetables, and selected fruit, such as strawberries and tomatoes [78]. Even if a city produced all the required volumes of these food types in indoor urban farms, it would still depend on food from peri-urban and rural areas for other food types. Nonetheless, the advancements in greenhouse design and production technologies are increasing the number of crops that can be produced indoor with high yields.

Tests and experimentations are leading the way for a growing offer of food crops that can be sold in urban areas. However, local regulations might limit the commercialization of this newly indoor produced crops, limiting for the moment their commercial development. In this scenario, research and development is fundamental to achieve maximum variety in urban crops production, as both costs and production data are needed to assess the economic feasibility of cultivating more variety of crops within the urban boundaries.

3. **Difficulties in becoming circular:** Finally, indoor urban farm types (multi-story soil-less hydroponic or aeroponic, greenhouse, aquaponics greenhouse, and hydroponic greenhouse) face challenges to becoming entirely circular [78]. High-tech soil-less farming methods require tailored nutrient solutions, where water pH and mineral nutrients concentration is manually or automatically controlled. Nutrients used in high-tech hydroponic greenhouses are mostly nitrogen, phosphorus, and potassium [17] coming from unsustainable sources, and, if not recirculated into the production system, they may cause environmentally dangerous runoffs. Furthermore, reaching high yields in indoor facilities require high energy inputs for lighting and heating/cooling, which at the moment are generally reliant on fossil fuels [78]. Nonetheless, technological innovation, as well as infrastructure planning strategies can help overcome these challenges as high-tech closed production systems have high potential in becoming completely circular. To do so, high-tech urban farms would need to:

- *Use renewable energy.* This would be more feasible if integrated into the spatial planning of the city, connecting them with the energy grid used by buildings, and, in case of new developments, to smart energy systems. One example encountered in the analysis of the case studies is the Bajes Kwartier, where the vertical farm is connected to the district smart grid that produces energy from renewable resources.
- *Close water loops.* To obtain a high degree of circularity for water and nutrients, the water used for irrigation must be of high quality [55]. Water sources that can be used come directly from the greenhouse, like drainage-water, from the environment, like rain-water, and from the urban context, like wastewater. Nonetheless, when reusing water from outer sources it is important to keep Na and Cl levels to a minimum, as solutes concentration in water would result in salt accumulation in the cultivation process. In large-scale urban food production systems, the use of disinfected urban wastewater might offer a valuable water source. However, to be able to safely reuse urban wastewater, indoor production must have the technologies that allow selective sodium removal, and more studies are needed on the long-term effects of growing media, soil, or plants [78]. Today, the best alternative water source remains rainwater, which can be easily collected from the greenhouse of building roofs and redirected in the production system. Thus, the collection and storage of rainwater may lead to an increase of circularity in protected cultivation systems [55]. Rainwater can be mixed with drainage and wastewater and stored in the proximity of the production area. Stored water must remain clean, thus ultrasonic treatment and UV sterilization systems must be used to avoid the spreading of pathogens coming from external sources.
- *Use nutrient inputs sourced from food by-products and outer sources*: Nutrients extraction, for both soil-less and traditional agriculture, is one of the most polluting human activities. Phosphorus and Nitrogen are essential and irreplaceable elements in food production, but unfortunately, phosphate fertilizer recovery from phosphate rocks is causing landscape degradation and a high amount of CO2 emissions due to recovery processes and fertilizer transportation, while nitrogen runoffs that are released in the environment contributing to air and water pollution. Nonetheless, cities are full of unexpressed potential for nutrients recirculation, being the greater consumers of food. Nutrients can be found in human excreta and in production by-products, two elements that if processed, can go back into the food system as fertilizer. Chapter 4 of this research will be fully dedicated to the advantage and limitations of nutrients recovery in cities, taking Amsterdam as a proposed case study.

In conclusion, the expressed potential for circularity in integrated high-tech protected agriculture in urban areas highly depends on the technical knowledge of the production systems. More technology and more control may lead to improved circular performances, but that requires high investments and a specific set of expertise that may not be easy to find in urban areas and in certain countries. Both UK and The Netherlands are innovators, and invested in research and development of those technologies that can improve circular food systems within their capital cities. Furthermore, optimal solutions for circularity have not been developed for all regions in Europe or the Mediterranean [55]. For instance, the closed or semi-closed greenhouse concept, fundamental for the circularity of the indoor food system, has been developed and is already applied by some Dutch greenhouses and cannot be directly transferred to the Mediterranean regions. That's because closed and semi-closed greenhouses in the Mediterranean climates require a lot of energy for cooling. Also, Decision Support Systems (DSS) for hydroponics have been mainly studied under Central and North EU conditions [55]. For these reasons, municipalities like London and Amsterdam in the Marine West-coast climates were able to carry on ZFarming projects and integrate them in circular urban planing strategies, as they already possess the technology and the know-how to manage and implement indoor production systems, integrating them in and on top of buildings. The two studied food strategies acknowledged that urban food production can not feed an entire city at the state of the art, but it can provide to increase food security in certain communities, as well as several high-value services to people in cities, including helping citizens reconnect with food and better understand where and how it is grown [78]. Reconnecting people with food, educating them to healthy diets, bringing production visible and tangible within the city boundaries, is considered crucial if cities want to change the way citizens see food, creating a ripple effect that may partially or drastically change modern food system. In this context, marketing strategies are fundamental for the acceptance of a new type of food grown without the constraints of the soil and integrated in buildings. That is why London and Amsterdam carried on strategies like changing advertisement policies and providing public buildings with locally produced food so that citizens may have a direct contact with their locally produced food. In particular, ZFarming initiatives can involve the participation of a great part of population, as they operate right there where people live and work. They can shape new architectural forms, and urban look, making food visible and livable for every citizen. Furthermore, in comparison with soil-based urban farming, ZFarming projects can directly connect food and architecture, exploring and developing those interconnected relationships where the two entities can exchange food, knowledge and resources.

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Chapter 4: Closing the loop of nutrients and water in ZFarming projects

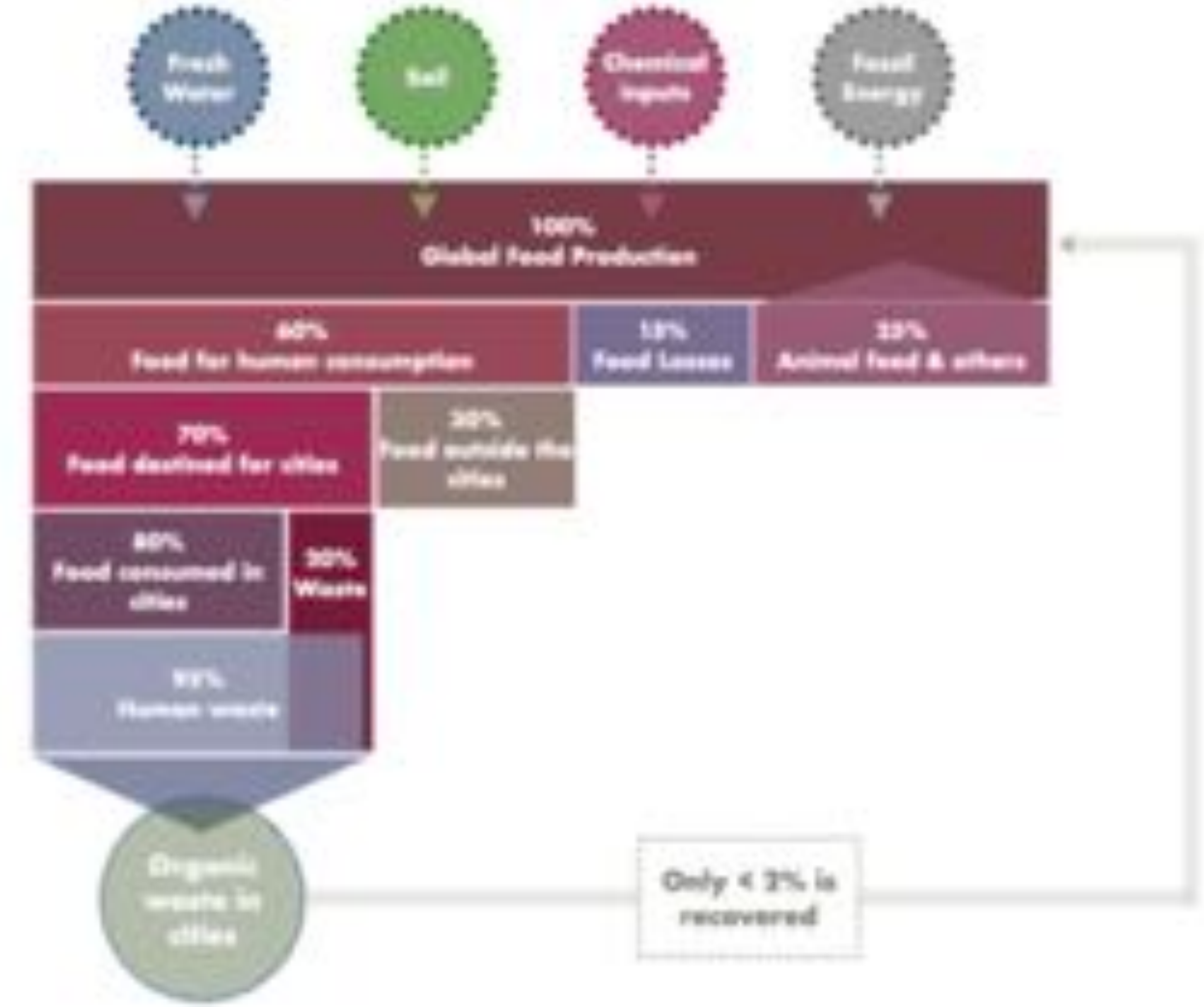
Preface:

The studies conducted in the first three chapters of this research contributed to demonstrate how UF is not just a food-related practice, but its implementation could actually be a boost for the development of new circular planning strategies in urban areas. Cities have resources, technologies and a ready-made market that can quicken the transition towards a circular food economy that will benefit the entire urban environment [1]. Furthermore, new technologies for soil-less cultivation can increase yields in limited urban areas not entering in competition with valuable building land. Nonetheless, the sustainability of high-tech production methods highly depends on the inputs that are used for plants to grow. In this scenario, recovery resources from buildings is a new opportunity for the development of sustainable high-tech ZFarming projects. Thus, a circular metabolism needs to be adopted in urban areas, relying on recovering, reusing and recycling resources where the outputs ('waste') from one metabolic urban entity can be translated into inputs for another. Both Amsterdam and London strategic development plans studied in Chapter 3, aim in this direction, focusing on recovering and recycling waste. On this trail, this chapter aims to answer the question "how can we re-use residential buildings' waste-streams as inputs for urban food production?", specifically focusing on closing the loop of water and nutrients in densely populated urban areas in West-coast maritime climates.

Currently, a major portion of the nutrients leaving agriculture is in the food products. Since the human body excretes almost all the nutrients that are consumed with food, urine and feces contribute to one of the largest fractions of the nitrogen and phosphorus flows in society [2]. Nutrients extractions, for both soil-less and traditional agriculture, is one of the most underestimated polluting human activity. Today, agriculture can partially be brought back to the city thanks to modern technologies and Urban Farming initiatives. This is a unique occasion to reuse important resources that will otherwise be lost. Indeed, nutrients flow is now a one-way flow where most of the matter is lost in the process (Fig. 1). However, cities present now an excellent opportunity to adopt a high-impact circular metabolism, in which outputs ('waste') from one process equals inputs ('resource') for another: urban wastewater cycle is one of the key processes connecting human activity to natural systems [3]. In this scenario, domestic wastewater reuse in agriculture through hydroponic systems can be a viable opportunity to avoid environmental and public health impacts**.** As reported in Chapter 2, in hydroponic systems, plants grow with the roots immersed in a nutrient solution or maintained through inert substrate within tanks supplied with formulated solutions of nutrients. Pathogen risks associated with wastewater reuse have been reported to be reduced in cases were edible crops are grown using hydroponic systems [4]. The advantage of these systems to minimize pathogen contamination is attributed to the fact that it allows different forms of technique such as water culture, drip irrigation technique (DIT) and nutrient film technique (NFT) which are capable at reducing risks compared to field applications were other irrigation systems like sprinkler irrigation is mostly used [5]. Therefore, hydroponic system is identified as one of the alternative technologies that can be integrated with wastewater treatment. The efficiency of a hydroponic system with regard to municipal wastewater reuse is mainly linked to its capacity to allow continuous use of wastewater through the production of agricultural crops and the removal of pollutants/nutrients (nitrogen and phosphorus), resulting to increased food security and environmental protection [6].

In soil-less growing systems, plants need water and nutrients to grow. In hydroponics, it is possible to achieve high yields and high qualities when water and nutrients are given at the required quantities. Nutrients and water required by the plants can be calculated [7] and accurately engineered. Nutrient solutions in commercial hydroponics fields are generally fixed, and many studies determined the best balance between water and nutrients for each specific crop [7]. Recently, a growing number of studies investigated how to extract nutrients from wastewater and use them directly in the hydroponic system [8].

Fig. 1: Linear flow of nutrients through city from production to consumption.



Source: *Own work based on Circular Cities..*
Cited sources: *FAOSTAT, Food Balance Sheets (2013); FAOSTAT, livestock manure (2013); WBA, Global Bioenergy Statistics (2017); The World Bank, What a Waste (2012); Scialabba, N., et al., Food wastage footprint: impacts on natural resources (2013), United Nations University, Valuing human waste as an energy resource (2015), Cities and the Circular Economy for Food analysis*

As a matter of fact, studies associated with the agricultural use of wastewater for plant production demonstrated that treated wastewater could be a good source of nutrients and irrigation [9]. In this scenario, the hydroponic system is one of the technologies that can contribute to wastewater recycling. Thus, the general idea that is expressed in this Chapter is to use the hydroponic system as tertiary treatment for wastewater recovery in residential buildings. This Chapter will present a review of the technologies that can be used to extract nutrients and fresh water from domestic wastewater, assessing the efficacy of the hydroponic system in respect of wastewater polishing when integrated directly in and on buildings in high-tech ZFarming projects. Finally, this chapter will evaluate the possible impacts of on-site wastewater nutrient plants in ZFarming projects on a relatively small urban scale: buildings or compound and small districts of 500-1000 inhabitants. The objective is to assess the minimal dimension of urban compounds for optimal resource recovery in order to fully comply with the vegetables demand of its inhabitants. These founding will constitute the design inputs for an integrated hydroponic system in urban environments which will minimize buildings' wastes through highly functional food production and will be described in Chapter 5.

1. Potential of Building-integrated agriculture: from food production to wastewater recovery

In the first chapters of this research it was reported how Urban Farming initiatives are rising all over the globe, aiming to locally feed a growing urban population, bringing farming concepts beyond food production, investing in different aspects of sustainable city development. Today, it became clear that the current food system, no matter how many significant productivity gains achieved over the past centuries, it is now unfit to meet long-term needs [1]. The industrial food system promoted during the first Green Revolution has dramatically increased global food production to meet rising demands from an increasing world population. That was achieved by adopting synthetic fertilizer and pesticides, monoculture high-yielding crops and modern fam machinery that on the long run depleted soils, polluted the air, and compromised fresh water reservoirs. Thus, the current food system has developed several negative societal and environmental consequences throughout the years, related both to consumption (i.e. obesity, malnutrition, and micronutrient deficiency) and production. Furthermore, the current linear food system is unsuited to face the challenges of climate change and resources depletion for several reasons that were explained in Part 1 and are resumed below:

- *It is very wasteful.* A third of all edible food continues to go uneaten, reaching the paradox where more than 10% of the global population suffer from severe hunger, while in Europe more than 25% of the population is obese, and in the U.S. this data grow to the point of 36%was [10]. Basically, waste is endemic to capitalistic agriculture overproduction, for instance, supermarkets regularly buy in stock 50 to 100% more food that they put on their shelves, that no customer can possibly buy. It is estimated that the equivalent of six garbage trucks of edible food is wasted every second. Furthermore, the displacement of production sites in respect to consumption areas causes that less than 2% of the valuable nutrients in food by-products and human waste produced in cities is recovered and recycled (Fig. 1). Instead, these nutrients are typically destined for landfill or incinerators or lay in open dumps, posing a serious threat for the environment. Recovering nutrients and food waste (both in the production and consumption stage) is a fundamental step for the transitioning towards a sustainable food system, and that is why food waste prevention has surfaced as a global agenda item, formalized by the United Nations' Sustainable Development Goal 12.3, which sets the ambition to halve per capita food waste and losses globally by 2030.

- *Pollutes the environment.* Pesticides and synthetic fertilizers used in conventional farming practices, along with bad management of manure, can exacerbate air pollution, contaminate soils, and leach chemicals into water supplies. Our food system today is the world's second largest emitter of greenhouse gases being responsible for approximately 26% of global GHG emissions [11]. The expansion of agriculture has been one of humanity's largest impacts on the environment. Through technology advances and the use of synthetic fertilizers, crop yields have increased significantly in recent decades, meaning that a lot of land has been spared from agricultural production: globally, to produce the same amount of crops as in 1961, only 30% of the equivalent farmland is required [12]. Nonetheless, monocultural intensive agricultural practices are causing an unprecedented impoverishment of soils' productive capacity, so that today it is estimated that every year agriculture is losing about 75 billion tons of crops soil. Furthermore, poor management of food waste and byproducts generated during food processing, distribution, and packaging further pollutes water [1]. Approximately 70% of global freshwater demand is used for agriculture and industrial agriculture is contaminating freshwater supplies, making the whole agricultural system vulnerable to the uncertainties caused by climate change. Possible solutions to overcome the problem might involve the return to organic agriculture where organic matter comes back to the soil, and the use of soil-less cultivations which can control the amount of water used for irrigation and that can reduce the use of chemical fertilizers. In this context, reducing pressure on soils through intensive off-soil agriculture practices such as hydroponic greenhouses and vertical farms can be an opportunity to transition towards a more soil-respectful organic agriculture. Furthermore, reusing water in agriculture is crucial to preserve our freshwater reservoirs. In this sense urban farming can count on multiple recycled water sources and can lead the way to sustainable usage of treated wastewater in urban areas.

- *Extracts finite resources and causes lost in biodiversity.* Since the beginning of the Green Revolution over 70% of the world's agro-biodiversity has been lost, meaning that local diversity is gone forever due to the use of just few commodity crops which replaced the the traditional ones who became indigenous in hundreds of years of natural selection [12]. The use of modified sterile crops is the cause for the loss of soils' resilience, and, all year-round monocultural crops are impoverishing the biodiversity of the grounds. Furthermore, the intensive agriculture machine requires huge amount of nutrients to keep producing food at this pace, so that vast amounts of phosphorus, potassium, and other finite resources are mined and extracted for farming. It is safe to say that the high environmental impact of agriculture on GHGs emissions is not only caused by the use huge amount of chemicals and fossil fuels, but also from its ecological footprint that causes the loss of vegetation, forests and soil organic matter. Processing, packaging, and distribution need tractors on the field and trucks on the highways, with the consequence that most activities in the food system are powered by fossil fuels [1]. It has been estimated that for every calorie of food consumed in the US, the equivalent energy of 13 calories of oil are burned to produce it [1]. In this context, making agriculture a local practice again is fundamental to reduce its impact on the environment, limiting the use of GHGs not only during the production phase, but also in all the following phases, from packaging to distribution.

In this chaotic scenario, cities are the greatest consumers of food. As shown in Fig. 1, today 70% of the whole food produced destined to humans is redirected to cities, and this number is bound to increase to 80% by 2050 [1]. Thus, cities are important hubs where a food revolution can take place. Today, a very high portion of food flowing into cities is processed and consumed there, generating high amounts of organic waste in the form of discarded food, byproducts or sewage. In our current linear system, only less than 2% of these valuable nutrients is reused and brought back as input for the food system. This is mostly due to the fact that places of production and places of consumption are very far apart from each other, making it almost impossible for recovered nutrients to find their way back through the food chain. Hence, implementing circular use of resources in urban areas, especially recovering nutrients from food waste, is a huge opportunity to dramatically reduce food production footprint, shifting towards more sustainable practices. In this scenario, Urban Farming initiatives can help transitioning towards a circular urban food economy, taking advantage of the already available resources in cities, using them for producing food in urban environment. Today, as demonstrated by the London and Amsterdam food strategies, it seems that customer preferences are evolving, people are becoming more health-conscious and governments and municipalities are planning a drastic shift towards plant-based protein diets in cities, investing in more regeneratively grown food, including UF practices in their spacial planning. In this sense, environmental improvements can be expected from such initiatives relating to: waste recycling; air quality; potential impact on the urban heat island; carbon sequestration; wastewater filtration; and impact on biodiversity [13,14]. Furthermore, integrating farming practices within the built environment might provide health benefits by recirculating resources from one urban entity to the other. Today, many resources passing through city buildings are wasted right after being used: a new green architecture should target this wasted resources and transform them into inputs for other urban activities, including urban agriculture as a full-fledge new construction technology. Moreover, merging architecture and agriculture is not entirely a new practice: historically, there has always been a link between the development of organized agriculture and the process of urbanization [15]. Nowadays, UA is taking advantages where Rural Agriculture (RA), the primary producer of food in cities, failed to achieve urban food security [15]. The concerns that modern practices of RA could deplete soils and that the process of land grabbing could cause a mass migration of rural populations towards urban areas, is triggering UA movements all around the globe, with a growing number of researches and publications in recent years [13].

Opposed to RA, UA mostly consist in small-scale initiatives due to the limited amount of space that can be found in cities. Thus, UA is unlikely to turn any city or most households fully self-sufficient in all of the food which they may require [9], and it must be seen as a complementary practice of industrialized agriculture. Nonetheless, recent studies [16][17] conducted in different European cities assessing the global scale of urban agriculture demonstrated that if implemented, its contribution to local vegetables production might reach peaks of 70 to 90%. This would mean converting all transformable cities' surfaces into farming spaces. And while this might be difficult, and even not recommendable, a lot of architectural spaces such as building's facades, rooftops and private areas [18], might be suitable for farming uses and the development of ZFarming projects.

Thus, integrating buildings with off-soil food production systems may improve building performances reducing waste to the minimum, while encouraging a small-scale, local urban food production (Fig. 2). In this scenario, the integration of hydroponic technologies in the same building premises represents an untapped opportunity to address two major circular challenges: i) nutrients recovery from wastewater; ii) wastewater treatment.

Fig. 2: The idea of a hydroponic wastewater treatment in BIA

Source: *Own work*

i) Nutrients recovery from domestic wastewater

Closing nutrients loop in cities in a major goal in Western European cities, as now there is the technology and the opportunity to operate concrete actions in urban areas. The importance of nutrients recovery is connected to the fact that nutrients extraction, for both soil-less and traditional agriculture, is one of the most underestimated polluting human activity. Phosphorus and Nitrogen are essential and irreplaceable elements in food production [19], and in the past century have been used to increase crops yield. The use of chemical fertilizers resulted in pressing environmental problems: on one hand, phosphate fertilizer recovery from phosphate rocks is causing landscape degradation and high amount of CO2 emissions due to recovery processes and fertilizer transportation [20]; on the other, Nitrogen environmental impact is very high due to the excess reactive nitrogen that is released in the environment contributing to air and water pollution [21].

Currently, a major portion of the nutrients leaving agriculture is in the food products. Almost all the nutrients contained in food products are excreted by the human body, therefore urine and feces contribute to one of the 'largest fractions of the nitrogen and phosphorus flows in society' [22]. This makes city buildings the greatest hubs for nutrient recovery. Unfortunately, as human excreta are mixed with other effluents (i.e. industrial wastewater, grey and rain water), it makes it almost impossible to recover usable nutrients when urine and feces reach the sewage. As a matter of fact, nowadays nutrients flow is a linear, one-way flow where most of the matter is lost after consumption. In this regard, using wastewater as fertilizer for agricultural purposes in urban areas can dramatically reduce nutrients and water waste. History proves that this is definitely not a new concept: in a not so far past, cities were located in proximity to the agricultural fields and human excreta, also known as 'night soil', was collected and then spread to the land as organic fertilizer, recycling back the nutrients [23]. Today, agriculture can partially be brought back to the city thanks to modern technologies and Urban Agriculture initiatives; therefore, it is now possible to directly re-use nutrients from human excreta as fertilizer reducing to zero transportation issues. In an integrated building-hydroponic systems, wastewater coming form the building can go under a primary and a secondary treatment to expel the solid matter and reduce pathogens, and finally reach the hydroponic system which will absorb the remaining pollutants contained in the water using them as nutrients.

ii) Domestic wastewater treatment

Wastewater treatment has always been one of the major urban challenges. Now that European mega-cities are becoming more densely populated, buildings and citizens are producing a greater number of waste streams. As a result, environmental and public health problems may arise from the insufficient provision of sanitation and wastewater disposal facilities [19]. Many wastewater treatment do not remove reactive nitrogen from the wastewater. Tertiary and final wastewater treatment are then required to meet environmentally-safe discharge standards, and while most of them rely on huge amounts of chemicals, new biological treatments are now developed and available. To this regard, hydroponic system are identified as one of the alternative technologies that can be integrated with wastewater treatment [24].

The efficiency of a hydroponic system with regard to municipal wastewater reuse is mainly linked to its capacity to allow continuous use of wastewater through the production of agricultural crops and the removal of pollutants/nutrients (nitrogen and phosphorus), resulting to increased food security and environmental protection [25]. Pathogen risks associated with wastewater reuse have been reported to be reduced in cases were edible crops are grown using hydroponic system. The advantage of this system to minimize pathogen contamination is attributed to the fact that it allows different forms of technique such as water culture, drip irrigation technique (DIT) and nutrient film technique (NFT) which are capable at reducing risks compared to field applications [26].

1.1 Characteristics and efficacy of the hydroponic wastewater system

Recovering nutrients from human excreta and wastewater has been receiving increasing attention as it represents a huge opportunity to replace synthetic fertilizers especially in urban areas. Improving nutrients management is key to minimize ecosystem damages caused by agricultural runoffs, and ensure food security and access to sufficient fertilizers [27]. In the hydroponic wastewater treatment, nutrients-rich wastes coming from municipal activities are used to fertilize plants, while plants are used as final treatment needed to polish wastewater and meet discharge/ reuse standards. Before undergoing the hydroponic treatment, domestic wastewater must be processed: first treatment is needed to remove the settleable solid from the wastewater preventing them to enter the second treatment which instead reduces the high level of pathogens contained in it. The benefits of integrating a hydroponic greenhouse the building premises and put it on top of the decentralized treatment plant consist in reducing transportation issues of the nutrient solution needed for irrigation, and a partial simplification of the the pre-treatment phases. To ensure better growing conditions, a state of the art greenhouse and/or indoor facility must be designed to satisfy crops requirements supplementing available natural resources such energy, heat and ventilation. To this regard three main factors will influence the hydroponic greenhouse design for the implementation of plants growth and wastewater treatment [25]:

1) *Open / Close system*: Shirly T. et al. determined that closed systems are the commonly preferred hydroponic systems for wastewater treatment as they can eliminate the discharge of contaminants to the environment. In closed hydroponic systems in-fact, it is possible to recirculate the same nutrient solution adjusting it accordingly to plants need at every cycle. Christie et al. [7] demonstrated that the recirculation of the drainage water, which is still extremely rich in nutrients, dramatically reduce environmental footprint and helps saving irrigation water. Nonetheless, even if close hydroponic systems are preferable for domestic wastewater treatment, when integrating them within buildings it must be taken into consideration that they require constant management as the nutrient solution must be monitored constantly to adjust pH, EC nutrients concentration and pathogens.

2) *Substrate selection*: Hydroponic systems fro wastewater treatment can be divided in to two main types [2]: (i) solution culture such as nutrient film technique (NFT), where treated effluents are pumped into a tank to the head of the NFT channels and plants are grown with their roots immersed into the nutrient solution that reaches them by gravity in a closed-loop system; (ii) media filled systems such as aeroponic plant growth systems, flood and drain systems, deep water culture systems. Haddad and Mizyed [19] experimented with both channels and media filled barrels in a closed hydroponic system. Results showed that media-filled systems are considered the simplest for hydroponic wastewater treatment, as they use growth media (rock-wool, stones and clay beads) for nitrification, and provided the best yields. Moreover, as reported by Gebeyehu et al. [28] they don't need separate bio-filtration, which is needed in NFT system to avoid clogging in the channels.

3) *Crop selection*: Selecting the right crops play a fundamental role in the functioning of municipal hydroponic wastewater treatment, not just because nutrients uptake varies depending to the plant, but also to promote and ensure acceptance of this technology in urban areas. Yang et al. [3] commented that vital criteria for plant selections in hydroponics depend on: (i) adaptability to hydroponic systems; (ii) availability in local context; (iii) relatively short life circle. Vegetables such as tomatoes, bell peppers, strawberries, cucumber, and lettuce and cut flowers are commonly used for hydroponic production due to their short growth cycle allowing better control and standardization of the cultivation process.

1.2. Effectiveness of the hydroponic wastewater treatment

In the past 15 years, researchers all over the world conducted different studies to assess the effectiveness of the hydroponic wastewater treatment. This study reviewed some of them to assess the feasibility of hydroponics when integrated in residential buildings, trying to understand how architects and planners could act in respect to these technologies. Results were reported in Table 1.

One of the first, and still most cited study, was conducted by *Vaillant et al.* (2003) [6], where primary municipal wastewater was treated using D. Innoxia plants as bio filters in an NFT hydroponic system with horizontal flow. The use of hydroponic system was effective at depleting COD, BOD and TSS[1] with percentage reductions of 82, 91 and 98, respectively. These results suggested that using a hydroponic system as a wastewater treatment can offer sustainable solutions for both ecological and environmental protection.

In 2004, *Norstrom et al.* [29] experimented micro-algal production in a hydroponic wastewater treatment in Sweden. The system used anoxic pre-denitrification followed by aerobic tanks for nitrification and plant growth. The results showed 90% COD removal was obtained early in the system. Nitrification and denitrification was well established with total nitrogen reduction of 72%. Phosphorus was removed by 47% in the process.

A study conducted by *Haddad et Mizyed* (2012) [2] in Palestine assessed the efficacy of a hydroponic wastewater system when cultivating flowers, vegetables and fruit trees. Findings showed that the hydroponic system is effective in reducing various pollution loads. Plant growth and pollutant removal were conducted in two different hydroponic systems: barrels and channels. Performance of hydroponic barrels was better than the channels; winter squash and trees showed a better growth and a better polishing than flowers and vegetables. The results obtained over three years of testing the initial design indicate 21 to 51% removal of BOD and 45–71% removal of COD. Total nitrogen removal was in the range of 13–47%. Total phosphorous removal performance was relatively poor (30%). After system modification to five consecutive treatments results indicated BOD removal of 93–96%, COD from 80 to 89%, and TN from 62 to 65%.

A 2015 study from *Yang et al*. [3] grew water spinach in a hydroponic system as final wastewater treatment in Singapore. The objective of the experiment was to meet local discharge standards using urine for plant growth and plants as urine polisher. Hydroponic experiments were conducted in a transparent PVC tank with 6 mm thickness and 800 mm x 600 mm x 100 mm (length width height) dimension. The tank was divided into three channels, each with 5 holes (D = 120 mm). The holes were packed with plastic pots which were filled with light-expanded clay aggregates as an environmental friendly material. Urine was collected from 30 adult males and then urease enzyme was added to enhance urea hydrolysis. After being pre-treated, urine nutrient solution was fed to the plants in different dilution ratios. This study demonstrated the feasibility of applying hydroponic systems for both urine treatment and water spinach cultivation. Plants cultivated in urine with 1:50 dilution ratio achieved the comparable growth characteristics (e.g., growth rate,

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[1] **COD:** *Chemical Oxygen Demand* analysis is a measurement of the oxygen-depletion capacity of a water sample contaminated with organic waste matter. Specifically, it measures the equivalent amount of oxygen required to chemically oxidize organic compounds in water. COD is used as a general indicator of water quality and is an integral part of all water quality management programs.

BOD: *Biochemical Oxygen Demand* analysis determine the aerobic destructibility of organic substances. It represents the quantity of oxygen which is consumed in the course of aerobic processes of decomposition of organic materials, caused by microorganisms. It provides information on the biologically- convertible proportion of the organic content of a sample of water.

TSS: *Total Suspended Solids* describes particulates of varied origin, including soils, metals, organic materials and debris that are suspended in a moving body of water.

leaf number, etc.) to those in the nutrient solution. Effluents concentration of 1:30 and 1:50 both met Singapore and European discharge standards.

Table 1: Effectiveness of different hydroponic systems in pollutants removal

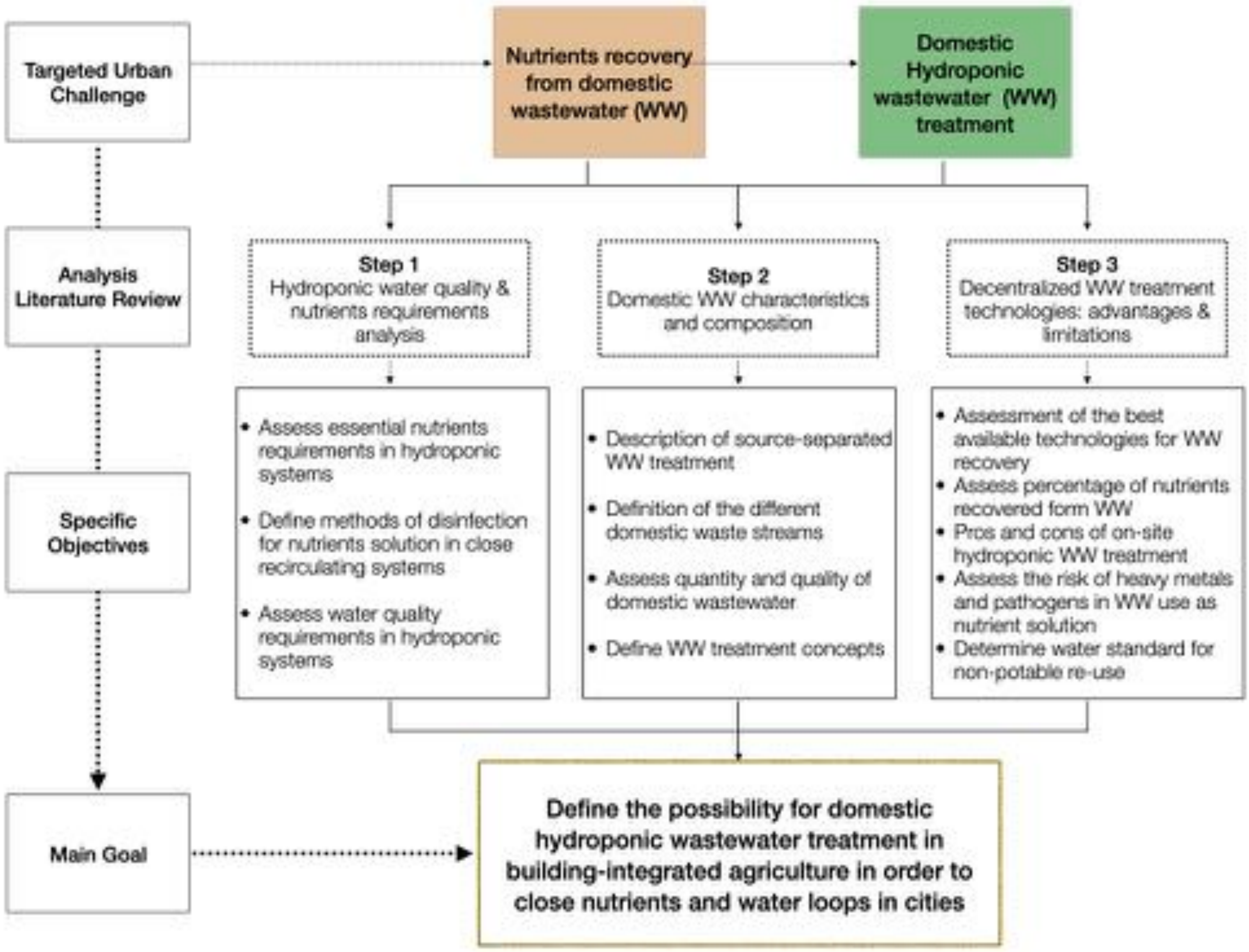
Study	Hydroponic system	Used Plants	% Removal
Vaillant et al. (2003)	Commercial hydroponic with Nutrient Film Technique (NFT) - horizontal flow	D. Innoxia	COD: 82% TSS: 98% TN: 93% TP: 38%
Norström et al. (2004)	Treatment plant using conventional biological treatment combined with hydroponics and micro-algae	Micro-algae	COD: 90% TSS: NA TN: 72% TP: 47%
Haddad et al. (2012)	Hydroponic horizontal channels	Cherry tomatoes	COD: 80% TSS: 95% TN: 86% TP: 52%
Haddad et al. (2012)	Hydroponic barrels	Citrus	COD: 67% TSS: 73% TN: 71% TP: 68%
Haddad et al. (2012)	Hydroponic barrels	Sweet corn	COD: 63% TSS: 81% TN: 93% TP: 49%
Yang et al. (2015)	Light plastic barrels with with clay	Water spinach	COD: 58.1-66.3 % TSS: 31.3-46.9% TN: 40.6-49.4% TP: NA

These studies showed how different experiments made in different areas of the world obtained similar results in pollutants removal when using a hydroponic system as final decentralized wastewater treatment. This largely depends on the fact that the hydroponic systems can be tailored to meet specific re-use/discharge requirements. In this regard, understanding the quantity and quality of the waste streams coming from the building is fundamental for the design of the integrated hydroponic system. Concentration of pathogens and heavy metals in the grown crops were not considered in these studies, even if they represent a critical parameter for the safe consumption of fruit and vegetable. Pathogens and heavy metals content in food produced with treated wastewater will then be investigated in the following sections of this Chapter.

2. Recovering nutrients from buildings. The methodological approach

Waste coming from residential buildings are demonstrated to be precious inputs for urban food production [25]. While a lot has been written on wastewater nutrient recovery for soil based agriculture, literature on nutrient recovery for urban hydroponic agriculture is quite limited. Due to its soil-less nature, and consistent higher yields per square meter, hydroponic agriculture is a valid solution for urban farming project [30]. This part of the research aims to review the benefits, concerning resource recovery in Building-integrated agriculture projects located in Center-Northern European climates - climatic area Cfb (Kottek et al. 2006) [30]. The objective is to extrapolate inputs for the integration of on-site wastewater systems in the design of new residential buildings.

After assessing the efficacy of the hydroponic wastewater treatment in the introductory part of the chapter though a systemic literature review, the following part of the research has been divided into three main steps as follows:



Step 1: *Hydroponic water quality & nutrients requirements analysis.* Nutrients are fundamental for plants growth in hydroponic systems. As they cannot be provided from the soil as in traditional soil-based agriculture, they must be supplied artificially and mixed with water, forming nutrient solution that can feed plants. During this step, essential nutrients and water quality requirements will be analyzed to assess optimal nutrient solutions targets that should be met in on-site domestic hydroponic wastewater treatment processes.

Step 2: *Domestic wastewater characteristics and composition.* Domestic wastewater is composed of different water streams flowing out from residential buildings, including grey-water from washing activities, black water, and urine from toilets. During this step, a differentiation of all water streams coming from residential buildings will be made. Subsequently, each waste stream will be analyzed for its chemical composition, based on which it will be possible to assess the best recovery strategies from domestic wastewater.

Step 3: *Decentralized wastewater treatment technologies: advantages & limitations.* Wastewater treatments are fundamental to meet discharge standards in cities, and several technologies to achieve pathogens removals from wastewater have been developed in the last century. Nonetheless, decentralized systems today can be coupled with hydroponic production to achieve on-site treatment, recovering nutrients from wastewater and use them as plants' feed. During this step, on-site wastewater treatment advantages and limitations concerning pathogenic content in treated wastewater will be analyzed to assess the feasibility of hydroponic wastewater treatment in building-integrated agriculture.

The final objective of this analysis is to determine if, and when, on-site hydroponic wastewater treatments can be favorably applied in Building-integrated agriculture projects, resulting in a real environmental gain for both urban food production and the development of circular green buildings and districts.

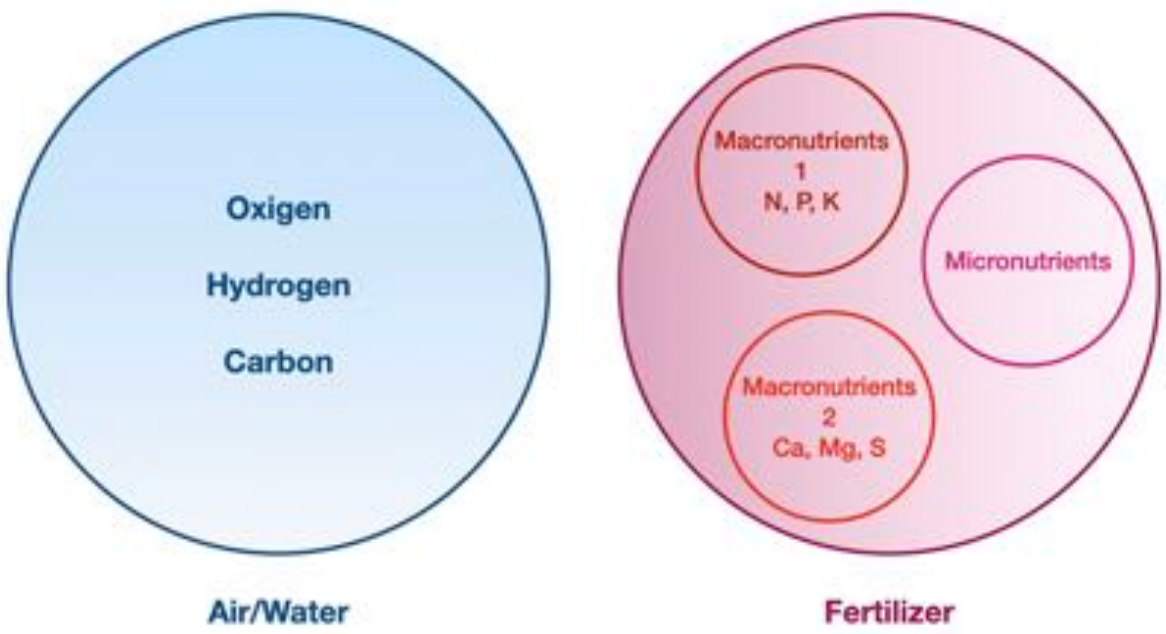
2.1 Water quality and nutrients requirements

Today, contemporary greenhouses use computer based methods to provide nutrient and irrigation controlling nutrient recipes based on each specific crop and water quality (salinity (EC) and pH levels) [31]. In each of the hydroponic methods reviewed in Chapter 3, nutrients are periodically and constantly pumped from a solution tank - positioned at one end of the system - into the channels or ‘beds’ where plant’s roots are submerged. Furthermore, in close systems, the excess nutrient is recirculated, flowing back into the nutrient tank and continuously pumped into the media until all the nutrients are depleted; meanwhile, EC and pH level of the nutrient solution must be constantly measured from recirculated drain water with specific measuring tools to maintain high quality of the nutrient solution. This specific practice of applying nutrients (fertilizer) to crops directly via the irrigation system is called ‘fertigation’ [32]. To be optimally effective and sustainable, fertigation requires good management through the entire process from the abstraction of water through to the management of irrigation water and nutrients applied to the crop [32]. In this sense, quality of water and content of nutrients are fundamental to reach perfect fertilizer recipe that will allow plant to grow healthy, reducing the risks for plant’s diseases.

Essential nutrients for hydroponics

Most plants rely on 16 nutrients to grow and reproduce [33]. Of these, three are available through water uptake and gas exchange (the air): *carbon* through CO2, *hydrogen*, and *oxygen*. The remaining thirteen nutrients are the mineral nutrients delivered to plants through hydroponic nutrients dissolved in a solution. They can be separated into 3 groups (Fig. 3):

Fig. 3: Essential nutrients for plants’ growth



Source*: Own work*

- Primary macronutrients, the most abundant building blocks in plant growth and reproduction.
- Secondary macronutrients, which are also necessary, but in smaller amounts.
- Micronutrients, which are required in very small quantities for growth and reproduction.

The primary group of the macronutrients includes Nitrogen (N), Phosphorus (P), and Potassium (K):

Nitrogen (N) is important for all kinds of molecules involved in photosynthesis and protein creation. It is supplied either all at once as in liquid fertilizers, or in two parts as in dry fertilizers. Nitrogen is absorbed by plants to produce amino acids, proteins, enzymes and chlorophyll [33]. The most used nitrogen forms for plant fertilization are nitrate and ammonium. Nitrates are quickly absorbed by the roots, are highly movable inside the plants and can be stored without toxic effects. Ammonium can be absorbed by plants only in low quantities and cannot be stored at high quantities because it exerts toxic effects [33]. If the quantity of Nitrogen provided to the plant is higher than 10 mg L calcium and copper uptakes are inhibited, further excesses in ammonia concentration result in phytotoxic effects [33]. Thus, if nitrogen is supplied in higher quantities, this could cause high vegetative growth, increase of crop cycle length, strong green leaf color, low fruit set, high content of water in the tissues, low tissue lignification and high tissue nitrate accumulation [33]. On the other hand, low nitrogen supplied quantities are characterized by a pale green color of the older leaves (chlorosis), reduced growth and senescence advance [33].

Phosphorus (P) is especially important to cell membranes and is supplied in the main nutrient mix, whether dry or liquid. Phosphorus stimulates roots development, the rapid growth of buds and flower quantity [33]. P is absorbed very easily and can be accumulated without damage to the plant. Its fundamental role is linked to the formation of high-energy compounds (ATP) necessary for plant metabolism [33]. Compared to Nitrogen and Potassium, the average quantities requested by plants are lower [34]. Nonetheless, in soil-less systems there are higher chances that P is not completely absorbed by the plants. This could be caused by lower substrate temperatures (< 13 C) or at increasing water pH values (> 6.5) which can lead to deficiency symptoms [35]. In these circumstances, studies reported how increasing substrate temperature and/or reducing pH in the water solution is more effective than adding amendments of phosphorus fertilizers [33]. Phosphorus deficiency causes older leaves to manifest a green-violet color, which may follow chlorosis and necrosis. On the other hand, P excess can reduce or even block the absorption of some other nutrients like Potassium and Iron [33].

Potassium (K) like phosphorus is delivered in the main nutrient mix. Potassium is fundamental for cell division and extension, protein synthesis, enzyme activation and photosynthesis and also acts as a transporter of other elements and carbohydrates through the cell membrane [33]. It has an important role in keeping the osmotic potential of the cell in equilibrium and regulating the stomatal opening [33]. The first signs of deficiency are manifested in the form of yellowish spots that very quickly necrotized on the margins of the older leaves. Potassium deficient plants are more susceptible to sudden temperature drops, water stress and fungal attacks [36].

The secondary group of the macronutrients includes: Calcium (Ca), Magnesium (Mg), Sulfur (S):

Calcium (Ca) is important to cell walls and is an important structural element. Calcium interacts uniquely with other nutrients, and it is much less soluble than the other nutrients, This means that it must be mixed separately [33]. Calcium is involved in cell wall formation, membrane permeability, cell division and extension [33]. When it is provided in the right quantities, Calcium gives the plant greater resistance to fungal attacks and bacterial infections [37]. The absorption rate is connected to the water flow between roots and aerial parts.Deficiency in calcium absorption or provision may cause stunted growth of the plant, deformation of the margins of the younger leaves, light green or sometimes chlorotic coloring of new tissues and a stunted root system without fine roots [33].

Magnesium (Mg) is important to the photosynthetic complex, and is involved in the constitution of chlorophyll molecules. Symptoms of deficiency are yellowing between leaf veins and internal chlorosis of the basal leaves [33]; magnesium-deficient plants will first break down chlorophyll in the older leaves and transport the Mg to younger leaves, due to the easies mobility of Mg. Therefore, the first sign of magnesium deficiency is the inter-veinal chlorosis in older leaves, contrary to iron deficiency where inter-veinal chlorosis first appears in the youngest leaves.

Sulfur (S) is required by the plant in quantities comparable to those of phosphorus, and in order to optimize its absorption, it must be present in a 1:10 ratio with nitrogen [38]. It is absorbed as sulphate [33]. The deficiencies are not easily detected, as the symptoms can be confused with those of nitrogen deficiency, except that the deficiency of nitrogen begins to manifest itself from the older leaves, whilst that of sulphur from the youngest ones. S nutrition has a significant role in ameliorating the damages in photosynthetic apparatus caused by Fe-deficiency [39].

The tertiary group of the micronutrients includes Iron (Fe), Chlorine (Cl), Sodium (Na), Manganese (Mn), Boron (B), Zinc (Z), Copper (Cu):

Iron (Fe) is one of the most important micro-nutrients because it is key in many biological processes such as photosynthesis [33]. To improve its absorption, the nutrient solution pH should be around 5.5–6.0, and the Mn content should not be allowed to become too high because the two elements subsequently enter into competition [33]. The optimal ratio of Fe– Mn is around 2:1 for most crops [40]. At low temperatures, the assimilation efficiency is reduced. The deficiency symptoms are characterized by inter-veinal chlorosis from the young leaves towards the older basal ones, and by reduced root system growth. Symptoms of deficiency are not always due to the low presence of Fe in the nutrient solution, but often they are due to the Fe unavailability for the plant. The use of chelating agents guarantees constant availability of Fe for the plant.

Chlorine (Cl) has been recently considered a micro-nutrient, even if its content in plants (0.2–2.0% dw) is quite high [33]. It is easily absorbed by the plant and is very mobile within it. It is involved in the photosynthetic process and the regulation of the stomata opening. Deficiencies, which are rather infrequent, occur with typical symptoms of leaves drying out, especially at the margins. To avoid crop damage, it is always advisable to check the Cl content in the water used to prepare nutrient solutions and choose suitable fertilizers.

Sodium (Na) if in excess, is harmful to plants, as it is toxic and interferes with the absorption of other ions. The antagonism with K, for example, is not always harmful because in some species (e.g. tomatoes), it improves the fruit taste, whereas in others (e.g. beans), it can reduce plant growth [33]. Similar to Cl, it is important to know the concentration in the water used to prepare the nutrient solution [40].

Manganese (Mn) forms part of many coenzymes and is involved in the extension of root cells and their resistance to pathogens. Its availability is controlled by the pH of the nutrient solution and by competition with other nutrients [33]. Symptoms of deficiency are similar to those of the Fe except for the appearance of slightly sunken areas in the inter veinal areas [33]. Corrections can be made by adding fertilizer or by lowering the pH of the nutrient solution.

Boron (B) is essential for fruit setting and seed development [33]. The pH of the nutrient solution must be below 6.0 and the optimal level seems to be between 4.5 and 5.5. Symptoms of deficiency can be detected in the new structures that appear dark green, the young leaves greatly increase their thickness and have a leathery consistency. Subsequently they can appear chlorotic and then necrotic, with rusty coloring [33].

Zinc (Zn) plays an important role in certain enzymatic reactions. Its absorption is strongly influenced by the pH and the P supply of the nutrient solution: pH values between 5.5 and 6.5 promote the absorption of Zn. Low temperature and high P levels reduce the amount of zinc absorbed by the plant. Zinc deficiencies occur rarely, and are represented by chlorotic spots in the inter veinal areas of the leaves [33].

Copper (Cu) is involved in respiratory and photosynthetic processes. Its absorption is reduced at pH values higher than 6.5, whilst pH values lower than 5.5 may result in toxic effects [33]. High levels of ammonium and phosphorus interact with Cu reducing its availability. The excessive presence of Cu interferes with the absorption of Fe, Mn and Mo. The deficiencies are manifested by inter veinal chlorosis which leads to the collapse of the leaf tissues that look like desiccated [33].

Without any one of the micronutrients, the plants will die or survive for only a generation or two. When plants produce seed, there is enough of some micronutrients in the seed to supply the plant that grows from the seed for all its life. But if plants doesn't acquire any of that micronutrient when it, in turn, is making seeds, then the next generation will be deficient and die.

Nutrients content in municipal wastewater

Studies over the content of municipal wastewater found considerable amounts of nutrients in it, especially macro-nutrients, such as phosphorus, nitrogen, and potassium. The analyzed studies that were cited in the introductory part of this Chapter found concentrations of total nitrogen (TN) and total phosphorus (TP) with the range of 30–41 and 4–9 mg/ L, respectively. According to these authors, nitrogen in wastewater is available in the form of ammonium ion, nitrate, and nitrite. Vaillant et al. (2004) [6] found a concentration of Potassium around 15 mg/ L in wastewater, concluding that both raw or treated wastewater contains some nutrients essentially for plant growth and development. This means that municipal wastewater is an important option for nutrients provision in hydroponic culture or aquaculture. However, the fertilizer effect (influent strength) of wastewater in hydroponics vary depending on the type of crop used, plant growth conditions, hydroponic substrate, the type/source of wastewater and the level of wastewater treatment (Table 3) [25].

Therefore, a study by Rose et al. (2015) [27] reported that several important factors must be considered when using treated wastewater as nutrient solutions in wastewater hydroponic systems such as: (i) nutrients availability; and (ii) solution pH for plant uptake. For instance, nitrogen in municipal wastewater is mainly in a reduced form and is not readily available for plants in hydroponics [25]. Thus, it is necessary that nitrogen contained in municipal wastewater would undergo some preliminary treatments to be transformed in its nitrate form, and therefore be utilized in hydroponics. In this context, technologies that can transform nutrients available in wastewater into nutrient that can be fully absorbed by plants are fundamental to exploit wastewater nutritive potential into hydroponic systems.

Nutrient solution's pH also influences the availability of nutrients in hydroponic system or soilless culture [41]. As reported in the essential nutrients analysis, water pH levels must not be higher than 6.5 or lower than 5.5. With higher levels of pH in nutrient solution plant will not efficiently absorb many essential nutrient like nitrogen, phosphorus, calcium and iron, which are already limited in wastewater hydroponic system solutions [42]. The nutrient solution pH is also reported to be influenced by the numerous factors, including, water quality (alkalinity), incorporation of mineral and organic compounds, plant species, nitrogen form, nutrient concentration and cation exchange capacity of the substrate are known to have an influence on the pH of a nutrient solution in hydroponic system [43]. These findings suggest that the quality of effluent used for irrigation in hydroponic wastewater system should be prioritized in the selection of hydroponic system for municipal wastewater treatment [44]. In this scenario, the quality of irrigation water is crucial to determine the degree of nutrients assimilation by plants.

Quality of water. Characteristics

The quality of the irrigation water is particularly important in hydroponic systems, affecting the effectiveness of nutrient solutions. Differently from soil-based agriculture, where roots can absorb nutrients from a larger root zone, in hydroponic systems the root space is restricted by the dimensions of the substrate which limits roots growth. Thus, roots will suffer immediately when nutrient solutions are not adjusted to accommodate water quality [32]. Often, water used for fertigation contains minerals and residual salts, it may have high pH levels or contain a high content of sodium [32]. In order to assess irrigation water quality for hydroponic systems, it is important to check three main parameters before proceeding with the composition of the nutrient recipe: i) pH levels in water; ii) salinity levels; iii) nutrients content in the irrigation water.

- **pH levels in water**. Assessing pH levels in hydroponic water is fundamental to guarantee optimal plants nutrient uptake. While in soil-based agriculture optimum pH for soils is from 6 to 7.5, in hydroponic systems optimum pH level in the growing medium should is lower, between 5.5 and 6.5. Several methods can be applied to prevent too high pH levels in the growing medium. First, check if the irrigation water pH is set at the correct level by checking the fertilization unit's pH setting, and monitor the quantities of acids actually being added to the mixing tank. The second method is to control the pH by increasing the ammonium level. This is done by adding increased amounts of ammonium to a nutrient solution when the pH in the root zone is rising, which usually occurs as a result of high vegetative crop growth rates [33].

- **Salinity levels.** Assessing the quantity of salt contained in irrigation water is crucial [32]. Sodium, in particular, is commonly present in water, but only small quantities are taken up by plants [32]. When irrigation water present an excess of sodium, this may cause salinity problems. Furthermore, crops damages may be caused by higher concentrations of sodium in the root zone. In this case, must a fraction of the recirculated nutrient solution must be discharged to prevent yield reduction or a decline in product quality [32]. Nonetheless, problems connected to nutrient solution discharge will result in unwanted losses of nutrients and water, and in environmental pollution.Water can be classified in three levels of quality according to the levels of sodium and chloride (Table 2,/).

Tab 2.1: Water quality levels

Quality level	EC (mS/cm)	Na/Cl (mmol/l)	Na (ppm)	Cl (ppm)	Suitability for hydroponic	Suitable uses
1	< 0.5	< 1.5	< 34	< 53	++	Suitable for all crops
2	0.5 - 1.0	1.5 - 2.5	34 - 57	53 - 87	+	Not suitable when recirculation is necessary
3	1.0 - 1.5	2.5 - 4.0	57 - 92	87 -142	+/-	Not to be used for salt sensitive crops

iii) **Nutrients content in the irrigation water.** Assessing the quantity of minerals that are already present in the irrigation water is crucial to determine the final nutrient solution recipe. Depending on the source of the irrigation water, in fact, it may already contain several minerals that are functional to plants growth. In this sense, the calculation of nutrient supplements must be done based on the quality of the water used, adding or subtracting nutrients taking into account the optimum values of the quantities of each element [33]. The final nutrient solution is then engineered n relation to the requirements of the specific crops and its cultivars considering plants' growing cycles and substrate.

In conclusion, once the irrigation water quality has been assessed, it is possible to proceed with the formulation of the nutrient solution. In literature, Maucieri et al. [33] identified three main steps for the composition of the nutrient solution:

1. First step is to define each specific cultivar requirements, taking into consideration the cultivation environment. For instance, in warm periods and with intense radiation, the solution must possess a lower EC and Potassium content, in spite a higher quantity of Ca; when temperatures and brightness reach sub-optimal levels, EC values and Potassium concentration must be increased, reducing instead those of the Ca.

2. Second step is to make the correct nutrient requirement calculations depending on the quality of the water use. It should be obtained by subtracting the values of the chemical elements in the water, and adding missing minerals following plants' requirements.

3. Finale and third step is to choose and calculate the amounts of fertilizers and acids to be used to balance the pH of the water. This way, optimal nutrients uptake from the plants is guaranteed.

2.2 Domestic wastewater characteristics and composition

New systems of sanitation and wastewater disposal facilities are an urgent matter to resolve in highly dense, overcrowded cities to limit environmental problems caused by an increasing amount of dangerous runoffs. In this scenario, it has been demonstrated how the use of domestic wastewater for agricultural purposes can be a way to kill two birds with one stone, dramatically reducing wastewater impact on the urban environment while recirculating high values fertilizers for UF activities. Domestic wastewater is, in fact, a gold mine of free macro-nutrients like Phosphorus, Nitrogen, and even Potassium, which are essential for crop production. In this scenario, hydroponic systems can be considered a valid alternative technology that can contribute to final wastewater treatments, allowing continuous use of wastewater through the production of agricultural crops and the removal of pollutants/nutrients, resulting in increased food security and environmental protection [33]. Reusing water and nutrients in urban areas is a chance to move beyond the concept of eco-efficiency and zero emissions [19], proposing new up-cycling models where elements and materials life-cycle is extended from one cycle to the other.

Nonetheless, reaching this goal in urban areas is far from granted. Planning strategies are needed to implement buildings and households with specific installations that allow separating water-streams avoiding cross contaminations. Furthermore, centralized or on-site wastewater treatment plans must be developed and built alongside hydroponic facilities to guarantee the maximum efficiency of the biological treatments. In this regard, a first step towards effective urban wastewater treatments the would be to provide households with source-separation and on-site treatment of domestic wastewater coupled with hydroponic and indoor off-soil facilities for food production. Domestic wastewater is, in fact, composed of several water streams that have different characteristics and present different levels of pathogenic content. For this reason, source-separation systems are acknowledged as one of the most promising approaches to optimize resource recovery [45].

New sanitation systems and for source-separation of water streams

Nutrients extraction and following disposal, has been reported to be an unsustainable practice: recycling nutrients from wastes back to urban agriculture is coherent with new planning strategies of minimizing ecosystem damage [46] ensuring food security in urban areas [27]. Today, resource recovery from wastewater is possible thanks to localized, source-separated sanitation systems, also known as new sanitation (NS). NS keeps streams separate and concentrated (e.g., low flush toilet, separation of black and gray water) minimizing mutual contamination and dilution of streams, which facilitates nutrient recovery [47]. In recent decades, localized, source-separated sanitation systems have been developed not only to treat wastewater, but also to recover resources from wastewater. New Sanitation (NS) is a new paradigm for the collection, transport, treatment, and recovery of solid waste and wastewater with the aim to recover resources (i.e. water, nutrients, organic matter), increase efficiency, reduce energy costs, and/or offer solutions to waste management [45]. New sanitation systems are especially interesting for neighborhoods, particularly for new developments or neighborhoods undergoing renovation, and larger commercial or public buildings [47]. As extensively written in this chapter, for the sake of this research only domestic waste-streams were taken into account.

With regards to source separated new sanitation systems, Wielemaker et al. (2018) divided domestic wastewater into [47]:

- **Black water** (BW), originating from toilet. When using a urine diverting toilet, it can be further divided into two more different streams: feces and urine.

- **Grey water** (GW), originating from shower, bathroom sinks, laundry and other washing activities.

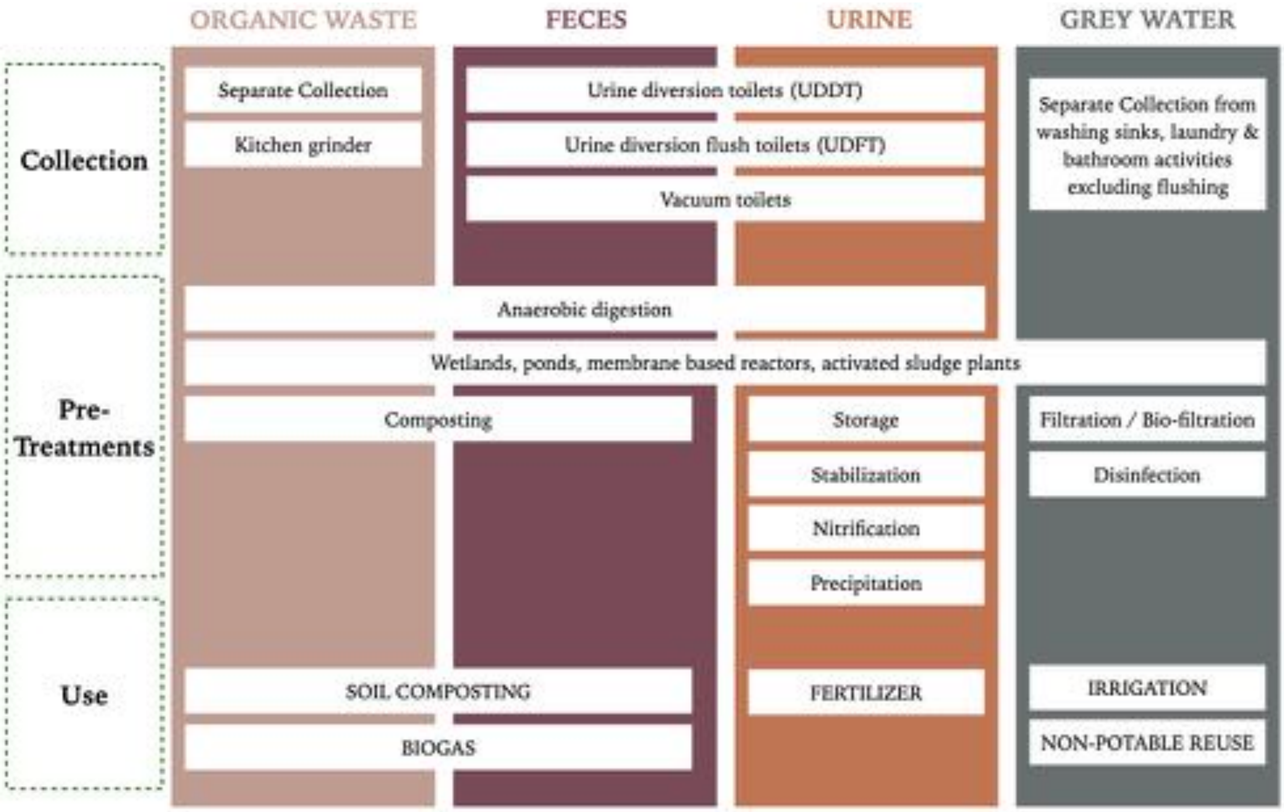
- **Kitchen refuse** (KR), that is solid organic kitchen waste disposed by a kitchen grinder.

Black water and kitchen refuse are considered concentrated streams, while grey water from washing activities, such as laundry, shower and bath is considered a less concentrated stream [9]. Black water can be further divided into urine and feces using urine diverting toilets or urinals. Nutrients can be recovered primarily from the concentrated streams, while the less concentrated stream serves as an alternative water source. Feces, urine and kitchen refuse (KR) contain the highest percentage of N, P, K and Organic Matter (OM). In particular, urine contains the most nutrients while kitchen waste and feces contain a lot of OM which makes them preferably usable for composting and soil conditioning [47] (Fig. 4).

Nutrients required for hydroponic systems are usually provided in a liquid solution, therefore OM coming from feces and kitchen grinders is usually not used as nutrient source in soil-less agriculture. Kitchen refuse and feces can then be collected together for either energy production (state of the art project: Water Hub @ NEST – decentralized and resource oriented wastewater treatment [48]) or composting for either rural or urban agriculture [19][47], therefore they won't be taken into consideration for the purpose of this research.

A research by Taina Tervahauta [19] and professor G. Zeeman from Wageningen University identified four sanitation concepts for domestic wastewater collection: (1) centralized; (2) centralized with source-separation of urine; (3) source-separation of black water, kitchen refuse and grey water; and (4) source-separation of urine, feces, kitchen refuse and grey water (Fig. 4). As reported by Wielemaker et al. (2018) [47], feces, urine and kitchen refuse (KR) are the best streams for nutrient recovery as they contain the highest percentage of Nitrogen, Phosphorus, Potassium and Organic Matter. In particular, urine contains the most nutrients while kitchen waste and feces contain a lot of organic matter which make them preferably usable for composting and soil conditioning (Tab. 1). As OM is not going to be used in the soil-less hydroponic system, it makes sense to divide urine from faces and kitchen refuse in order to collect as much as usable nutrients as possible.

Fig. 4: Wastewater streams - collection, treatments and use

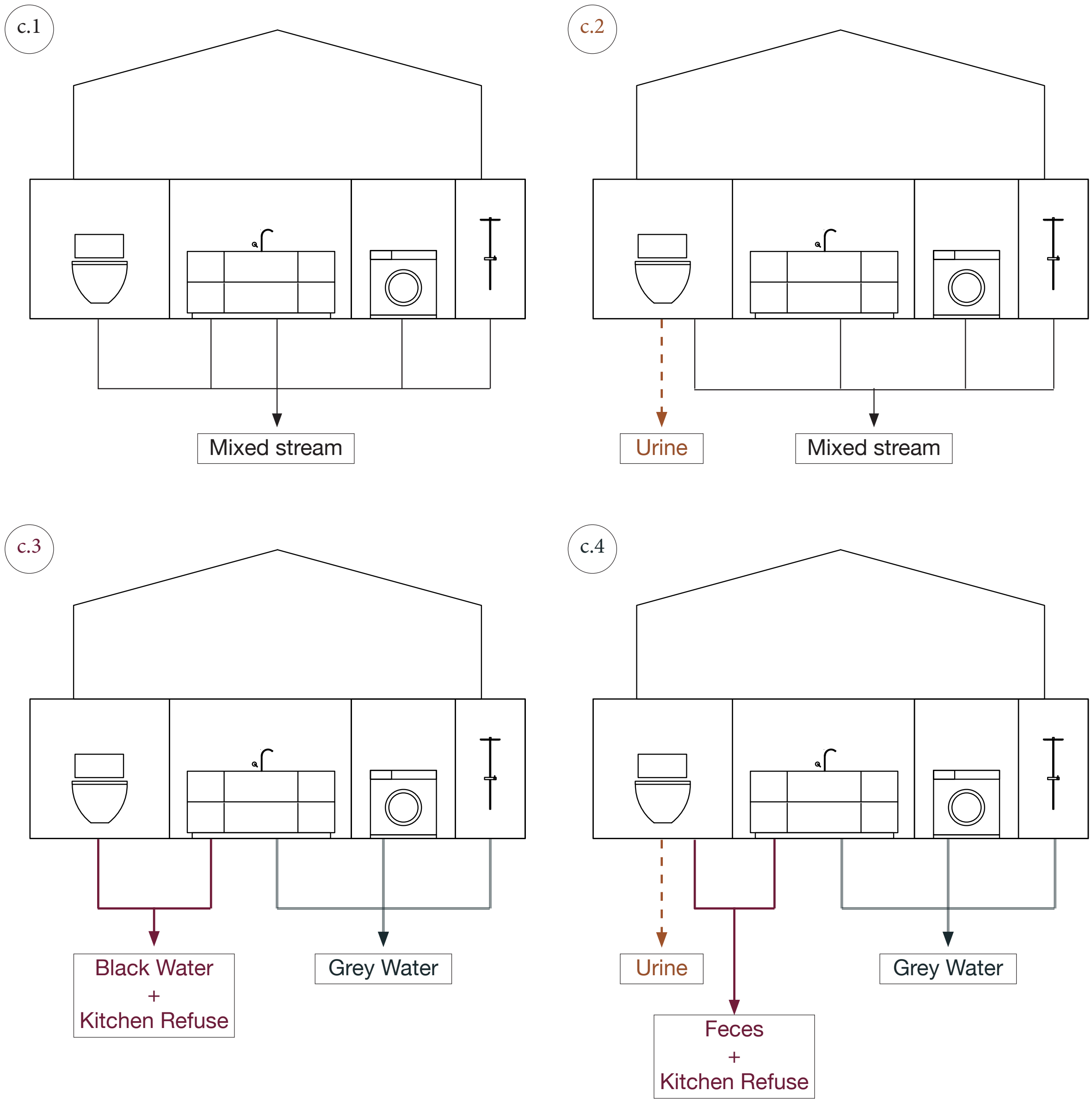


Source: *Own work*

Based on the above mentioned research, *Concept 2, 3 and 4* work as source separation of domestic wastewater. This system provides an opportunity to collect the toilet waste separately, implementing nutrients collection. At the sam time, the system collects grey-water. Grey-water alone has a much lower concentration of pathogens than when combined with domestic wastewater. Moreover, GW constitutes most of the wastewater quantity in households' wastewater. Grey-water separation from blackwater offers chances to treat most of the wastewater easily using on-site treatment systems to a quality that can be discharged to local water recipients or reused for a non-potable purpose without negative effects on health and the environment when treated properly. GW is collected from kitchen and bathroom sinks, showers, and laundry. On the other hand, BW consists of urine, fecal material, toilet paper, and flushing water from the toilet. In addition to the two broad classes, urine can be collected separately as yellow water using urine diverting toilets [25]. Approximately 80 % of nitrogen and 45 % of phosphorus and 55% of potassium are contained in urine stream, which constitutes only 2% of the wastewater volume.

In this scenario, *Concept n.1* and *n.2* were not considered favorable for the purpose of this research as they won't separate grey-water from black-water. *Concept n.3* is not optimal as fecal cross-contamination of urine during and after excretion can increase the number of pathogens in urine which represents the highest source of nutrients for plant production [49]. Moreover, heavy metal concentrations in urine are generally very low in relation to the nutrients while feces constitute a much higher heavy metal load compared to urine [50].

Fig. 5: Sanitation concepts for source-separated domestic waste-streams collection

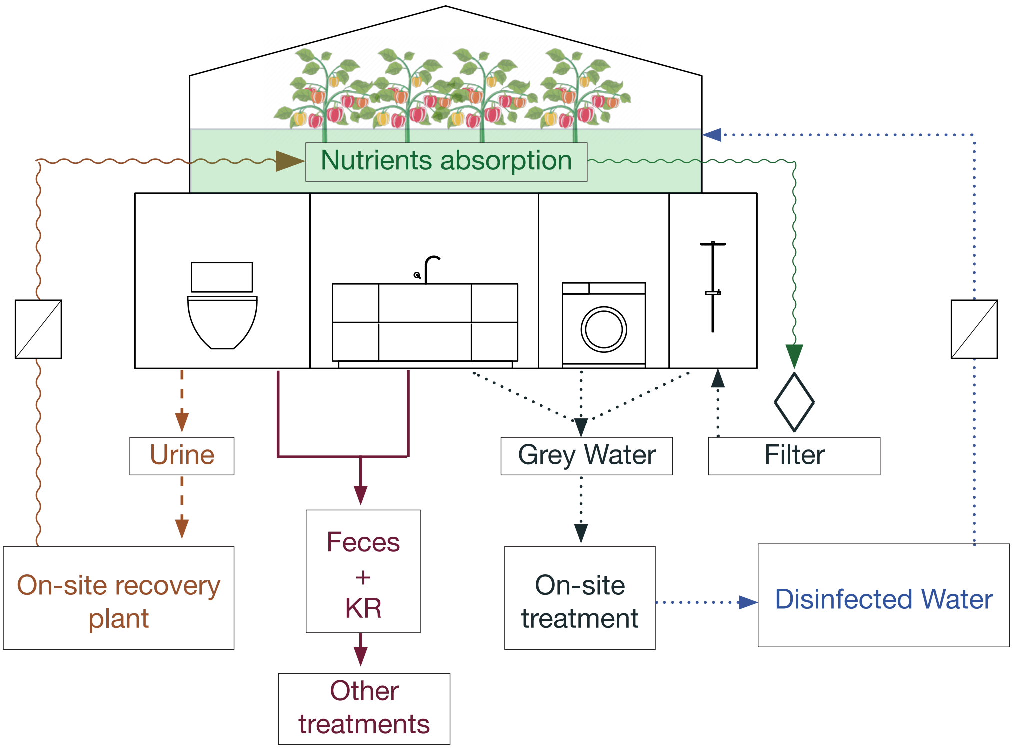


Source: *Own drawings based on Taina Tervahauta [19]*

Therefore, based on these consideration, NS *Concept n.4* seemed to be the more appropriate for hydroponic wastewater treatment, where urine is collected and nitrified [35] while feces and KR can either be discharged or used as organic matter for soil-based UA practices (Fig. 6).

Nonetheless, to be effective this concept requires specific urine diverting toilet types that must be installed in households [19]. The installation of source-separated toilet diverts urine from feces, making it more effective to recover and reuse nutrients [45]. The great opportunity given by the use of source-separated sanitation systems is that almost all nutrients contained in urine can be used for plant growth, and plants serve as bio-filters for urine polishing. The urine diversion toilet is a dry, double chamber toilet. Feces and urine are separated at source by way of a specially designed pedestal. The separation of the excreta at the source makes it easier to process the different streams as they are relatively pure. Furthermore, without the presence of urine in the chamber, the solids can dry faster and are easier to handle meanwhile the urine is directed to a soak-away and used to make nitrified fertilizer. Knowing the quantity and quality of urine and grey water is crucial to assess on-site hydroponic wastewater treatment strategies. As the quality of both urine and grey water is strictly connected to people habits and diets, it is necessary to know the context in which wastewater treatment is designed for. For the purpose of this research, all the data reported below will refer to Dutch domestic wastewater.

Fig. 6: Source-separated wastewater integrated with the hydroponic system. Concept.



Source: *Own work*

Composition of domestic wastewater: Urine

Human excreta contains most of the nutrients required for plant growth and when combined with hydroponic solutions they can be a valuable resource instead of useless waste to be discarded. Nutrients such as N, P, K are essential for the growth and development of crops in hydroponics, seed formation within the crop, maximizing flower numbers as well as transportation of sugars [30]. The majority of the macronutrients are found in the urine fraction with the contribution of about 80 % of nitrogen, 45 % of phosphorus and 55% of potassium [45]. Nitrogen, phosphorus, potassium and calcium are the major plant nutrients required for the plant to maximize fruit quality yield. Thus, urine represents the best nutrients source in wastewater streams. The nitrogen contained in urine is mainly in the form of ammonium with 85–100 % of it being plant available, same as in chemical fertilizers [3]. Urine additionally contains many other nutrients important for plant growth, such as sulphur, boron and magnesium. However, urine accounts for less than 1% of total wastewater volume (Fig. 7). In this regard it is fundamental to separate urine stream from the other waste streams. To do so, the installation of urine-diverting flush toilets (UDFT) is fundamental in the design of new or restored buildings. Current research on UDFTs is developing newer, more efficient models such as *"save!"* designed by studio EOOS in cooperation with LAUFEN and *Urine-diverting dry toilets* [4]. Research, development and installation of new sanitation systems and urine diverting toilets is a crucial step to close nutrient loops in urban areas.

Frequency and composition of urine streams is variable, and depends on cultural habits, local diets and municipal water quality. For instance, according to the study *'Identifying Amsterdam nutrients' hotspots'* [50], Dutch citizens spend on average 76% of their time in their homes on a weekly base and 72% of the urine is excreted at home. Based on this data, Wielemaker et al. (2019) [50] esteemed a domestic urination frequency equals to 5 times. Using a urine diverting toilet, where each urine flush equals to 0.2 L [50], it was possible to assess an average urination per capita of 1 Liter per day. Estimating the quantity of urine expelled during a specific amount of time is crucial to assess the quantity of nutrients that can be recover from the source. In this regard, contexts and habits of different urban population are important data to know to assess the effectiveness of the system.

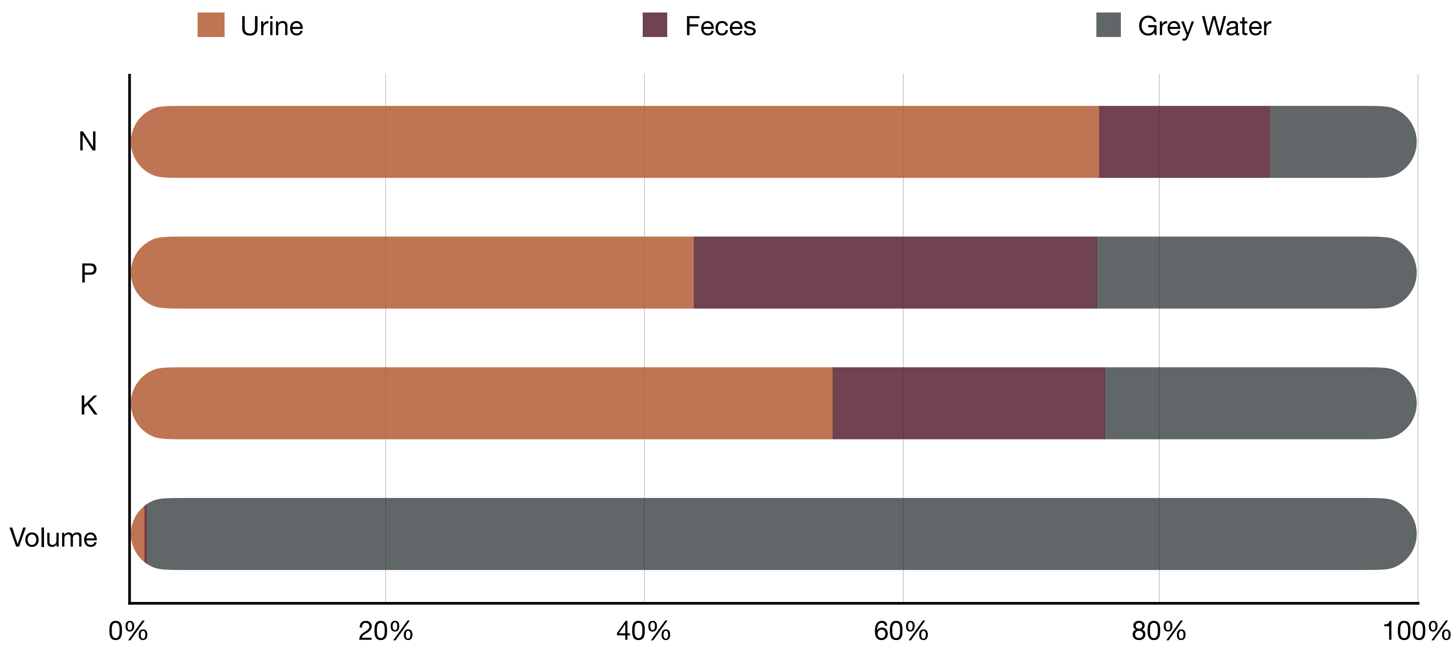


Fig. 7: Composition of domestic wastewater
Source: *Own work based on [30]*

Composition of domestic wastewater: Grey Water

Grey water coming from source-separated wastewater systems has a much lower concentration of pathogens than combined domestic wastewater, and constitutes most of the wastewater quantity in households' waste streams: more than 90% of wastewater volume is, in fact, produced by the less concentrated stream coming mainly from washing activities, such as kitchen, laundry, shower and bathroom sinks (Fig. 3). Therefore, recovering grey water represents a great opportunity to dramatically reduce water waste in urban areas. Despite of its reuse potential, there are certain concerns regarding the reuse of grey water, in particular with respect to the risks of direct or indirect exposure to pathogens and toxic compounds in the case of insufficient treatment of this stream [25]. In this regard, the integrated hydroponic system can be used as final treatment to remove the last pollutants (mostly nitrogen and phosphorus) before the recycled water is used again in non potable applications such as washing, flushing and irrigation.

The composition of grey water varies, and it is largely a reflection of the lifestyle and the type and choice of chemicals used for laundry, cleaning and bathing. The quality of the water supply and the type of distribution network also affect the characteristics of grey water [34]. For instance, according to Foekema et al. [35] daily water consumption in the Netherlands was 127.5 L per capita. Deducting the water use for drinking and toilet flushing, according to Lucìa Hernandez [33], Dutch grey water production amounts to 88.6 L per person per day. Pollutants content of grey water and urine is reported in Table 2,0, showing the amount of nutrients available per day in Dutch households.

Tab. 2.2: Final composition of domestic wastewater - urine & grey water

Parameter	Unit	Urine	Grey Water
Volume	L/p/day	1,0	88,6
COD	g/p/day	7,2	52
TSS	g/p/day	41,0	55
TN	g/p/day	7,9	1,2
TP	g/p/day	0,7	0,4
TK	g/p/day	1,8	0,8

2.3 Decentralized wastewater treatment technologies

First decentralized wastewater systems were developed in the late 1800s as wastes disposal facilities for isolated individual homes which had no pipe connection to the centralized urban system. In the past thirty years, research over decentralized systems has sparkled and today on-site plantations are not only considered a viable alternative but present some advantages over centralized systems [36] such as:

(i) the use of shallow, water-tight infrastructure, not subject to corrosion, that can be installed, maintained and repaired easily;

(ii) the ability to eliminate stormwater and other inflow sources;

(iii) the implementation of source separation in decentralized systems is relatively easy compared with the collection and management of separated waste streams and allow immediate resource recovery before the mixed streams reach the sewer.

Reported limitations [36] consist in the use of relative high energy inputs and the physical footprint required. Nonetheless, due to its advantages, on-site wastewater treatment has recently moved from rural areas, to urban fringes finally reaching dense urban centers: green buildings initiatives has started to promote the use of decentralized wastewater systems, generally in the form of water recycling and nutrients recovery, to reduce overall water use aiming to reach zero discharge goals. Technologies for on-site nutrient recovery and pollutants removal from domestic wastewater associated with an integrated hydroponic system are currently being improved and developed. Two main case studies found in literature were deeply analyzed in the following paragraph, showing a comparison between two different but effective approaches for wastewater preliminary treatments in connection with hydroponic facilities.

	Advantages	**Disadvantages**
On-site wastewater treatment facilities	Easy to install and maintain	Relatively high energy inputs
	Limited risks related to external inflow sources	Physical footprint
	Allow immediate resource recovery before wastewater reach and get mixed in the sewer	May occupy valuable building land in urban areas

On-site nutrient recovery processes for urine

In a very recent article, Shirly Tentile Magwaza [44] reported how commonly used nutrient recovery methods have been applied in wastewater treatment thanks to the development of a wide range of innovative technologies that allow nutrients recovery from human waste. Most cited technologies involve struvite precipitation (crystallization) from source separated urine [51], forward osmosis [52], ammonia stripping [53] and nano-filtration for the separation of heavy metals from nutrients in source separated urine [54]. While these strategies may have been applied to recover nutrients from human excreta, they are impractical for onsite application because they bring additional energy cost and results in CO2 emissions [44].

In this regard the use of decentralized waste-water treatment system, nitrification and distillation process, and hydroponic system for the cultivation of agricultural crops using nutrients recovered from human waste is recommendable for on-site use [45]. Environmentally, hydroponic crop production can also be used as final treatment of source-separated human urine to meet the sewer discharge standards [42]. In an integrated wastewater treatment incorporating hydroponic production, nutrient rich effluents from the treatment of urine or wastewater can be used to grow plants [44]. Combining these systems has been reported as an effective method to address the challenges of waste disposal in urban settlements, with the advantages of increasing food production in urban agriculture.

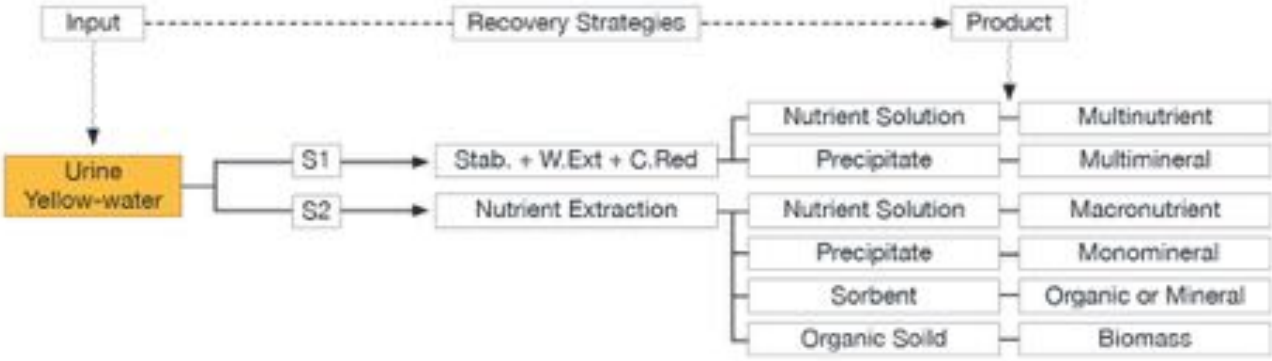
Studies on hydroponic wastewater treatment demonstrated a removal efficiency of 58–66 % chemical oxygen demand (COD), 41–49 % total nitrogen and up to 47 % total soluble solids indicating sufficient capacity for nutrient removal in urine [46]. Although P: N and K: N ratios in urine based fertilizers are relatively lower compared to synthetic fertilizers, the ionic form of both phosphorus and potassium makes it readily available for plant absorption upon application [43].

According to R. Harder et al. (2019) [32] nutrients recovery from urine or yellow-water represent two broad strategies (Fig. 7.2):

- S1: The first strategy aims at prevention of ammonia volatilization, separation of water from nutrients, and/or contaminant reduction.

- S2: The second strategy is characterized by selective nutrient extraction. Treatment processes applied to this end often also imply volume reduction (through separation of nutrients from water) and contaminant reduction (through separation of nutrients from contaminants).

Fig. 7.2: Conceptualization of the two main strategies for nutrients recovery from yellow-water



Source: R.Harder et al. [32]

In this scenario, best strategies for urban on-site nutrient extraction from human urine would be to use easy compact and manageable state of the art technologies. An experiment conducted in South Africa from Shirly Tentile Magwaza seems to propose a valuable solution for urine nitrification. In this experiment, the production of nitrified urine concentrate (NUC) was done according to Udert and Wachter (2012) study [45]. Nutrients contained in the source-separated urine were stabilized by means of biological processes (nitrification and distillation). The liquid was concentrated 20 fold to produce a high nutrient content fertilizer. The product is reported to contain comparable amounts of nutrients with most chemical nitrogen fertilizers [43]. The concentrated liquid is produced via nitrification of the urine in a moving bed biofilm reactor (MBBR) followed by vacuum distillation. However, nitrification process may be more complex than other recovery methods such struvite precipitation, which is a simpler method that has been widely used to recover phosphorus from urine. To better assess advantages and disadvantages of two different approaches to nutrients recovery from urine, two recent case-studies were analyzed and compared with an extensive literature review on the topic of decentralized wastewater treatment. In this regard, the two major pre-treatment processes that have been found in literature and that could provide a complete nutrients recovery from urine are:

i) *Struvite precipitation*: the first process starts with phosphorus recovery through induced struvite precipitation.
ii) *Nitrification:* the second process starts from nitrogen recovery through nitrification.

Case study 1: P recovery

In the previously cited experiment made by Yang et al. [21] in Singapore, researchers grew water spinach in a hydroponic system as final wastewater treatment. After collecting urine from 30 adult males the, pre-treatment process consisted in:

a) *Add urease enzyme to enhance urea hydrolysis*. As the direct application of hydrolyzed urine is phytotoxic, two more steps followed to treat urine for hydroponic irrigation

b) *Induced struvite precipitation*: Struvite precipitation is a proven technology to recover phosphate from wastewater and has also been applied successfully to recover P from source-separated urine [37]. Generally, the magnesium contained in wastewater or urine is comparatively in lower quantities than nitrogen and phosphorus [15]. Accordingly, a source of magnesium is added to optimize the crystallization process of struvite. If magnesium (Mg) ions are dosed correctly, nearly 100 % of the phosphate can be precipitated. However, ammonium recovery in struvite may be only 5 % and other valuable nutrients, such as potassium (K), sulfur (S), and micronutrients, are not recovered [38]. Given that struvite precipitation recovers mainly phosphorus, but only limited amounts of nitrogen and other micronutrients, additional treatment has to be provided, in order to achieve a satisfactory effluent quality. Struvite precipitation advantages concern the limited space for application, an easy manageable systems which require very low energy inputs.

c) *Ammonia air-stripping:* Stripping is the most common process for the selective recovery of ammonia from wastewater [39]. In many research applications it is combined as second treatment of struvite precipitation to recover ammonia and nitrogen from struvite effluents. In air-stripping processes, air is forced through urine to catch the gaseous ammonia. In most cases, the air is then injected into a tank containing sulphuric acid, which at its turn, reacts with the gaseous ammonia to form an ammonium sulphate solution [40]. Ammonia stripping can be considered to be a proven technology for nitrogen and ammonia recovery from source-separated urine. However, as reported by Siegrist et al. (2013) [39] this process need strong bases and acids for the air stripping/acid adsorption and this represents a great challenge for small decentralized reactors [39]. According to this study, small on-site reactors will probably not achieve the high energy efficiency of large-scale reactors and thus concluded that ammonia stripping is a suitable process for medium-sized reactors that treat the urine of several hundred people.

According to this study, pre-treated urine content of nutrients has a lower concentrations of many nutrition elements (N, P, K, Ca, etc.) compared to commercial fertilizer, however they were sufficient for plant growth during the experiment. Plants fed with 1:50 pre-treated urine dilution ratio exhibited the best physical characteristics and showed a comparable growth with commercial nutrient solution. As a conclusion it is possible to examine two major impact pre-treated urine nutrient has on the hydroponic system:

1. *Plant growth:* Plant Growth Rate (PRG) and Plant Leaf Number (PLN) increased with decreasing concentration of ammonia-nitrogen. The Plant Water Content (PWC) value in urine with 1:50 dilution ratio was similar to that in the nutrient solution, indicating comparable plant growth effects. Conversion rate in macronutrients such as N and P was double comparing to commercial nutrient solution showing better utilization efficiency. Nonetheless, it was reported that the joint addition of micronutrients such as B, Zn and Mn would result in a significant enhancement of plant growth.

2. *Pollutant removal efficacy*: COD is an important parameter to assess the effectiveness of wastewater polishing [21], this experiment reported a 58–66% remotion of COD at different dilution ratios. Nonetheless, only concentration in the effluents with 1:30 and 1:50 dilution ratios met European and Singaporean discharge level. The reported higher P and N conversion rate provably depended on the lowest concentration of P and N in the pretreated urine. However, this means that while hydroponic wastewater coming from commercial nutrient solutions must undergo other treatments such as nitrification-denitrification, pre-treated urine fertilizer meets required nitrogen discharge standards.

Case study 2: N recovery

Magwaza. et al. [41] used nitrified urine concentration (NUC) and effluents from a decentralized wastewater treatment plant (DEWATS) as separate nutrient sources for hydroponically grown tomatoes in South Africa. Urine was collected from source-separated toilets and transformed into concentrate urine fertilizer. To extract nutrients from urine the researchers from this experiments used a system patented by VUNA (Valorization of Urine Nutrients for Africa) . VUNA is a spin-off of EWAG, Swiss Federal Institute of Aquatic Science and Technology and developed. The system has been installed and implemented in three locations: i) Forum Chriesbach – Eawag's main building (CH), ii) Newlands-Mashu Field Test Site (SA), and iii) eThekwini Prior Road Customer Care Centre (SA) [40]. The nitrification process is divided into [42]:

a) *Stabilization through storage:* Urine is a highly concentrated solution containing about 80% of the excreted nitrogen. In toilets, pipes and storage tanks, urea, which is the main nitrogen compound, is hydrolyzed: after urea hydrolysis, 90% of the total nitrogen is converted into ammonia [43]. Stabilization of urine is specifically directed to prevent volatilization of ammonia as this can help avoid N losses and negative impacts associated with released ammonia gas [27]. Stabilization of fresh urine aims at preventing urea hydrolysis and hence preserving N in the form of nonvolatile urea. Stabilization has been reported to be a standalone process, but for a better nutrient recovery it is generally applied in combination with storage processes, and used as pretreatment to other processes, like evaporation and distillation [27].

b) *Nitrification:* The term nitrification is used to describe the biological oxidation of ammonia to nitrate. Nitrification is a suitable process to stabilize nitrogen in urine. Approximately 50 % of the total ammonia contained in stored urine is transformed to nitrate by bacteria in a Moving Bed Biofilm Reactor (MBR). Simultaneously, about 90 % of the organic matter is degraded. The resulting liquid is free from malodor and can be distilled without losing ammonia via volatilization [40].

c) Distillation: Udert and Wächter (2012) [44] demonstrated that distillation could be used to concentrate nearly all nutrients, if urine had been nitrified. This process is needed to obtain a concentrated liquid fertilizer: the stabilized urine is distilled to approximately 3 to 5 % of its initial volume into a concentrated liquid that contains all the nutrients from urine. Distilled water, which represent 95 to 97% of the initial solution, is recovered and can be reused for non-potable uses such as flushing or irrigation.

From the nitrification + distillation process, researchers of the VUNA projects developed an organic fertilizer, AURIN, which is currently being distributed in Europe and reported results in crops yield comparable with commercial synthetic fertilizer. In the experiment in South-Africa human excreta-derived NUC used for growing tomatoes reported low crop growth and yield compared to the chemical hydroponic fertilizer mix. Plants treated with NUC produced lower shoot dry mass (13.90 g) and root dry mass (4.70 g) compared to the plants treated with commercial fertilizer with the mass of 44.56 g and 12.23 g, respectively [45]. On the other hand, NUC has demonstrated to have a positive effect on mineral nutrition and physiological functioning [41] showing high conversion rates. The efficiency of these nutrient sources on photosynthetic capacity over commercial hydroponic mix lies on the fact that these nutrients contain a high amount of essential nutrients, such as N, P, K and Ca, which are efficient for the process of photosynthesis. Unlike most chemical fertilizers, human excreta based nutrient sources contains all the micro nutrients necessary for plant growth, even though the integration of micronutrients such B, Mn, and Zn might enhance crops growth.

Nitrification and Struvite precipitation. A comparison

When compared, both methods have advantages and disadvantages that make them more suitable for different applications (Tab. 4). In this sense, small variations in respect to the reported case studies have been found in the literature assessing the application of nitrification and struvite precipitation with regards to the scale of their application [36] (Fig. 8).

For instance, the nitrification reactor developed by the researchers from EWAG was sized to treat yellow water for a maximum of 500 people. Nonetheless, the last stage of Distillation was mainly thought to prevent high volumes of water, reducing specific weight of the concentrated nutrient solution and thus eliminating high transportation costs of the treated fertilizer. When urine nitrification is applied to smaller buildings, or compounds, the nutrient-rich water coming from the nitrification process could be directly redirected to the hydroponic system, avoiding the high-energy demanding process of distillation. In this case, the distillation phase could also be substituted by pasteurization processes that require lower energy inputs. Following the same principle, storing urine followed by struvite precipitation can be an effective and low-cost process to recover P from urine in small settlements and single houses, eliminating the ammonia stripping process. Complete struvite precipitation plus ammonia stripping is, instead, an efficient solution for bigger scale projects such as districts or neighborhood.

In conclusion, both pre-treatment processes showed a good capacity for nutrient recovery, and their applications with final hydroponic systems are reported to be promising. Reported advantages and disadvantages of the integration of these systems within the residential building are listed in Table 4. The choice between one method or the other must follow economic, spatial, and design considerations. Added material concerning the characteristics and applications of urine Nitrification and Struvite precipitation is reported in the annexes attached to this Chapter.

Table 4: Advantages and disadvantages of complete nutrient recovery systems

Pre-treatment process	**Concept**	**Equipment**	**Advantages**	**Disadvantages**
Struvite Precipitation + Ammonia air stripping	90% of P is recovered from the precipitated liquid. The effluent from the struvite process must undergo an air stripping process for N recovery.	• Manual / Automated struvite reactor • Air Stripping reactor	• Struvite reactors are relatively cheap and easy to use/maintain • The process guarantee a good P and N recovery • If properly diluted, the efficiency of the concentrated nutrients is comparable to commercial fertilizers	• Air stripping needs strong bases and acids for the air stripping / acid adsorption • Small scale on-site reactors might not be energy efficient • Most micronutrients are lost in the recovery process
Nitrification + Distillation	During nitrification 50% of ammonia is transformed into nitrate. The effluent from this process is rich in nutrients which can be distilled into a concentrate liquid fertilizer	• Urine storage tank • MBR reactor for nitrification • Vacuum distiller	• Complete nutrients recovery • Complete sanitization during distillation • Compact dimensions of the whole system (5 sm) • The distillate water is ready-to-use for irrigation or non potable purposes	• Higher energy demand in comparison with a struvite reactor • Complexity of the system which requires monthly maintenance

Fig. 8: Different applications of Nitrification and Struvite Precipitation based on the scale of intervention

Single & Raw houses 1 to 50 ppl	Buildings 50 to 100 ppl	Building clusters 100 to 500 ppl	Small districts more than 500 ppl
Suggested process **Storage + Induced struvite precipitation**	Suggested process **Nitrification + pasteurization**	Suggested process **Nitrification + Distillation**	Suggested process **Induced struvite precipitation + ammonia air-stripping**
Advantages: Low cost application Small energy requirements Easy operable technology	Advantages: Complete nutrients recovery Very low risk for pathogens Small dimensions of the whole system	Advantages: Complete nutrients recovery No risks for pathogens Concentrated liquid solution extraction No pipe transportation needed Scalable system	Advantages: Complete macro-nutrients recovery High efficiency of the system Requires low power to operate
Disadvantages: Only P is extracted N loss in the process No micronutrients contents Not self-sufficient for food production	Disadvantages: Medium energy demand High complexity of the process	Disadvantages: Higher energy demand High complexity	Disadvantages: Micro-nutrients are not recovered High dimensions of the air-stripping reactor

Source: *Own work*

Pathogens risk assessment associated with urine recovery

Both analyzes case-studies showed optimal performances in terms of nutrient extraction (TN, TP, TK) and pollutants removal such as COD, BOD, TSS. Nonetheless, assessing the content of pathogens present in treated yellow water is crucial for its use for agriculture irrigation. As previously written, humans excrete most of the pathogens in their bodies via faces rather than urine. However, even if urine is collected from urine-diverting toilets, it still may be contaminated with faces and can, therefore, contain pathogens (bacteria, viruses, helminths, and protozoa) [55]. Furthermore, some pathogens are also present in the urine of infected persons. Such pathogens in stored urine could seriously compromise the safety of urine collection systems and the quality of their fertilizer as end product [55].

In this regard, researchers from the VUNA project collected and analyzed urine samples taken from the urine storage unit and investigated possible treatment processes. This is a fundamental operational step when planning on using urine fertilizer. In this regard, several methods to assess the presence of viruses or bacterias in yellow water can be used to detect them. The first step to treat urine for pathogens is to determine the duration of the storage period. Both analyzed case studies stored urine before the chemical treatments, which indicates that storage is a crucial step to remove pathogens and stabilize urine. During this step, the pH of the urine rises due to urea hydrolysis [36], increasing the concentration of ammonia which is a deterrent for pathogenic microorganisms [55]. However, storage periods can't be too long, and in general, they are not sufficient to effectively inactivate pathogens. Chemical processes activated by struvite precipitation can cause the disappearances of most viruses and bacterias, but may not be completely effective on others. In this sense, the study conducted by Yang et al. (2015) [3] stated that however promising, direct consumption of cultivated plants as edible food is feasible but will require further investigation [3]. Indeed, cultivated plants should be tested for food safety, such as pathogens heavy metal, and micro-pollutant accumulations [3]. On the other hand, during the VUNA experiment, researchers demonstrated that nitrification processes are ineffective to inactivate pathogens, while the only effective method is distillation. Here, nitrified urine is heated up to 80 degrees, which is the common temperature used to pasteurize commercial food products [55].

In conclusion, the distillation stage of VUNA proved to be highly effective in inactivating pathogens in urine, but struvite precipitation will need additional treatment. Furthermore, other than assessing the presence of dangerous pathogens in urine, another limitation may be the presence of other residues such as pharmaceutical pollutants. Thus, before using yellow water as fertilizer, a complete chemical and physical assessment of pathogens and pollutants present in the urine composition is crucial to safely use urine-based fertilizers.

On-site nutrient recovery processes for grey water

Domestic grey water represents about 95% of total volume of buildings' wastewater and for this reason it has been increasingly used as an alternative water source to reduce potable water demand and to alleviate pressure on sewerage systems [56]. Due to its characteristics, which make light grey water the least polluted of domestic wastewater streams [57], it requires minimum treatment which makes it suitable for on-site treatment and re-use schemes.

Currently, many on-site technologies are applied for grey water treatments such as filters, fixed film reactors, rotating biological reactors, membrane bioreactors, sequencing batch reactor and wetland systems [56]. The development of these technologies allowed to minimize risks associated with pathogens and bacteria in treated grey water. Nonetheless, in recent years, new biological treatments, also known as Nature-based technologies (NBS) for grey water treatment, have been developed with the advantage that they can operate under low energy and low maintenance requirements, thus, reducing CO2 emissions compared to original treatment plants [57]. For instance, the wetland system is one of the most known of such technologies, but it requires certain dimensions that may be an impediment for this system to properly operate in highly dense urban areas, making it not suitable for small scale on-site treatments. Nonetheless, principles of bio-filtration comparable with the wetland concept could be now applied and operate with a smaller footprint, presenting a great opportunity for on-site grey water recovery in residential buildings. In this regard, New Sanitation technologies helped developing these technologies allowing to use grey water together with urine for the irrigation of a hydroponic greenhouse.

Hence, living walls and green roofs can be integrated together with the bio-filtration system to polish grey water before irrigating the integrated hydroponic systems. Green, vertical and horizontal surfaces presents many advantages when integrated in urban environments such as building energy savings, acoustic isolation, and cooling [59]. Both green walls and green roofs can be considered as modified applications of traditional constructed wetland systems as they are based on the same fundamental principle, which is coupling the biological, chemical, and physical processes within porous media enhanced by plants and microorganisms [57]. In this regard, the efficiency of these systems in wastewater treatment is connected to a strong interaction among plants, biofilms, substrate, atmosphere, and nutrients from wastewater [57], favoring different fundamental mechanisms of pollutant and pathogen removal, such as sedimentation and filtration as physical processes, precipitation and adsorption as chemical processes, and microbiological degradation and plant uptake as biological processes [57]. However, while green walls and green facades have been profoundly studied, yet few literature has been dedicated to their capacity to treat municipal grey water. Only recently, a greater number of studies have demonstrated that grey water-treating green walls have significant potential for on-site grey water treatment [57]. Green walls and roofs are then to be considered effective systems for on-site grey water treatment, fostering further urban benefits including microclimate, aesthetics and amenity benefits, increasing urban biodiversity and reduction in the adjacent building energy consumption [56]. In this sense, green surfaces adjacent to buildings walls and roofs can implement the architectonic quality in ZFarming projects, providing first treatments for grey water that can then be used as irrigation water for the integrated hydroponic systems, completing the loop of water and nutrient recovery in densely populated urban areas.

In order to assess the efficacy of theses systems in grey water polishing, two case studies concerning plants species and dimensions of the living walls were analyzed and reported below.

Case study 1: Ornamental flowers and climbers for living walls

This Australian study, conducted by Harsha et al. [56] (2017), aims to investigate a range of ornamental flowers and climbers as living walls for grey water treatment. For the purpose of the experiment, 70 laboratory columns made of 240 mm PVC pipe were set up in an open-air greenhouse with a clear impermeable roof. The PVC pipes were filled with sand to avoid preferential water flows. A total of 11 plants (divided into climbing plants and lower storey ornamentals) were chosen based on their ability to tolerate water-logged conditions, a high nutrient environment, and elevated salinity (Tab. 5).

Different plants were chosen as they play an important role in pollutant removal, presenting species-specific pollutant removal efficiency [60, 61].

Tab 5: Selection of plants for grey water experimental treatment

	Climbers	**Non-climbers**
Vegetation type	*Vitis vinifera* (Grape vine)	*Strelitzia nicolai*
	Parthenocissus tricuspidata (Boston Ivy)	*Phormium spp*
	Pandorea jasminoides	*Canna lilies*
	Billardiera scandens	*Strelitzia reginae*
		Lonicera japonica
		Carex appressa
		Phragmites australis (perennial grass)

The design of the living walls included lower-positioned saturated zones, working as bio filter columns that may help plants survive during dry periods, as well as improve pollutant processing [62]. Two saturated zones were analyzed and compared: the first one was designed based on current stormwater biofiltration guidelines [63], while the second one was appositely designed to improve nitrogen removal efficiency through promotion of rapid denitrification [56]. Light synthetic grey water was fed into the bio filter columns five days per week in a one-year period (October 2014- October 2015), except for two resting periods of 2.5 weeks in April and July and one resting period of just one week in June. In the high flow rate experiment each column was dosed once a day with 5 L with a detention time[2] of 48 h for practicality. For the low flow rate experiments each column received 2.5 L of greywater five days per week with an equivalent detention time of 96 h.

Water samples were collected eight times throughout the entire duration of the experimental periods, monitoring columns' performance under different conditions. Both inflow and outflow

[2] **Detention time** is the amount of time it takes for a drop of water to pass through a basin or a tank. It is calculated as the ratio between volume and flow rate.

sample were collected and analyzed for BOD, TN, ammonium, oxidized nitrogen, TP, filterable reactive phosphorus (FRP), total dissolved phosphorus (TDP), TSS, total organic carbon (TOC), and dissolved organic carbon (DOC). With regards to pollutants removal, analysis showed that after treatment, effluents from all experimented living wall satisfied local guidelines for unrestricted urban reuse related to the “non-potable applications with uncontrolled public access” (<10 mg/L) and environmental reuse (<30 mg/L) in terms of BOD requirement [64]. TSS also resulted in satisfying removal quantities depending on the selected plants. In this regard, it seems that the effluent from the greywater system can be successfully used for restricted urban applications during the system's first year of operation [56]. Total pathogen removal obtained by the experiments is reported in Table 6.

Tab. 6: Performance of grey water treatment designs after 12 months of experimentation expressed in percentage (%)

Saturated Zone type	Plant species	TSS	TN	TP	FRP	DOC	TOC	BOD	Infiltration rate (mm/h)
Standard	*Lonicera japonica*	95	89	**34**	60	82	82	98	
	Parthenocissus tricuspidata (Boston Ivy)	94	82	**19**	**33**	77	76	96	
	Pandorea jasminoides	95	97	**14**	**29**	79	77	98	
	Billardiera scandens	-	-	-	-	-	-	-	
	Strelitzia nicolai	94	85	24	28	80	80	98	
	Phormium spp	93	55	**7**	**-15**	82	81	98	
	Canna lilies	95	85	49	80	77	75	99	
	Phragmites australis (perennial grass)	94	**7**	**24**	**8**	86	86	98	
	Carex appressa	89	91	67	87	84	83	98	
Novel design	*Strelitzia reginae*	92	**23**	**16**	**-3**	88	89	99	
	Vitis vinifera (Grape vine)	88	92	53	45	83	83	99	
	Carex appressa	94	92	85	86	71	73	96	

From the analysis of Table 5, it can be noted how BOD, TOC, TSS, and TN removal was consistent in all design types and with minor differences between all the experimented species. When using *C. appressa* in both saturated zones there are no appreciable differences caused by the bio filter design. In contrast, FRP removal efficiencies varied to a larger extent across plant species. Only *C. appressa*, *Canna lilies* and *L. japonica* demonstrated high FRP removal efficiency (>80%) over the duration of the experiment. This might be and indicator that these three specific plant species have a high nutrient demand and a more efficient nutrient uptake. In this study, most influent TP occurred as FRP due to the synthetic grey water composition, as such, similar results for TP and FRP removal were expected. Compared to nitrogen then, phosphorus is retained in the system with the possibility to reach starvation stages and thus be leached in the effluent. Regarding EC and pH that were not shown in the table, there was not an appreciable differentiation in quantity between influent and effluents: effluent EC was mostly not significantly different from the influent EC ($p > 0.05$); outflow pH was stable at 6.13 - 7.14 with a median of 6.83.

Concerning infiltration rate (IR)[3], different dosing quantiles were given to each plant species. IR was measured five times from May to October. The infiltration rate was calculated as the average decrease in water level over the measurement period (measurements were taken every 75 second for a total period of 20 minutes). After the comparison of IR at the beginning of the experiment with IR measured at the 12th month no differences were appreciated, suggesting that clogging events may be caused by plants' bio-mass production rather than by the accumulation of organic matter present in the suspended solids. Nonetheless, it was noted that certain plants showed greatest difficulties recovering in IR after the resting periods. Plants that performed better were *C. Lilies*, *Grape vine*, and *S. reginae*. However, calculating IR rate is important to prevent clogging in the system, but it appears not to be a factor influencing removal performances, since plants mantained consistent removal percentages both in the lowest and highest IRs.

The efficacy of Hydraulic Loading Rates (HLR)[4] in grey water treatment were also measured by comparing two different flows: a faster one of HLR = 110 mm/d with a retention time (HRT) of 48 hours; and a slower one of HLR = 55 mm/d with HRT of 92 hours. No differences TN and FRP removal were shown when changing HLR and HRT, meaning that rapid nutrient processing is taking place within these systems and that the system is still within its HLR limit at 110 mm/d. However, it was noted how infiltration rates decreased during winter, hence, plants showed signs of stress with higher HLR. For this reason, this study recommend to use a lower HLR when possible.

In conclusion, the analyzed study wants to give informations for the future design of living walls for grey water treatments, but acknowledged that field applications will provide more reliable data, using actual grey water and not a synthetic imitation. Nonetheless, lab results demonstrated that suspended solids and organics removal was excellent in any sand-based living wall system (>80% for TSS and >90% for BOD), suggesting that living walls are a valid treatment technology for grey water reuse. Furthermore this study provides with useful insights for operating and design living walls:

1. A system infiltration capacity of 200 - 400 mm/d was found to be satisfactory in this study. To prevent system clogging in the event of increased non biodegradable coarse particles, it is strongly recommended to install a pre-treatment device, for instance, a mesh screen, before grey water entry into the bio filter.

2. For nitrogen and phosphorus removal, selection of plant species is a more important design criterion. Plants that performed better were *C. appressa*, *Canna lilies* and *L. japonica.*

3. *C. appressa*, *Canna lilies* and *L. japonica* were also the least affected by changes in operational conditions and seasonal changes in the early years of system operation.

4. Lower HLR of 55 mm/day is recommended. Also, having a larger system will also prevent surface ponding in the event of high flows, preventing retention odors. This can occur especially in winter when IRs are lower.

5. The study stated that if a long-term target of TP removal higher than 60% the living wall system will not be solely sufficient. Nonetheless, for the purpose of this thesis, the incorporation of the hydroponic system will work as tertiary treatment for Phosphorus removal. Furthermore, as urine has lower concentration in P than in N, irrigation water with higher P concentration might provide a more efficient nutrient solution.

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[3] The **infiltration rate** is the velocity or speed at which water enters into the soil or medium. It is usually measured by the depth (in mm) of the water layer that can enter the soil in one hour. An **infiltration rate** of 15 mm/hour means that a water layer of 15 mm on the soil surface, will take one hour to **infiltrate**.

[4] **Hydraulic loading rate** means the **rate** at **which** wastes or wastewaters are discharged to a land disposal or land treatment system

Case study 2: Green walls height and design strategies

This other Australian study by Prodanovic et al. (2020) [64] aims at defining what would be the optimal design of a green wall for greywater treatment, and what dimensions should be adopted to optimize pollutant removal. To answer these questions, researchers from three universities in Australia compared the performances in greywater treatment of two widely commercialized green walls: pots and blocks. Pot design consists of individual containers filled with media hosting a single plant, while block design consists of a larger block unit that contains media and multiple plants. To assess the efficacy of these two systems in polishing greywater and remove bacterias, two experiments were conducted in a specially constructed open-air greenhouse that was exposed to local temperature and humidity conditions of Melbourne, Australia, while being shielded from the rain.

S1: Pollutants removal
The first study aimed at assessing pollutants removal capacity of the two green wall systems, determining which one of the two would guarantee the best performance. A Gro-wall® 4.5 system was used for pot design, where pots were filled with media with the plant inside. The system was set up to host three vertically aligned pots, each hosting a single plant that would not interact with the adjacent ones. Greywater was dosed from the top part of the system and collected at the bottom for the outflow analysis. The system was supported by a custom-made vertical wall, imitating real-life applications. Five vegetated and four non-vegetated (media only) were used during the experiment. Block design was made using circular PVC pipes, which dimensions replicated the ones used in pot design (Tab. 7). Three holes were made in the pipe and covered with felt to prevent soil media to come out. Plants were inserted by making an incision in the felt and were given a total of 18L media mix (6L each plant, equivalent with pot design). Treated greywater was collected at the bottom. Equally to pot design, five vegetated and four non-vegetated configurations were set up. In order to compare results, pot and block designs were set up at the same time removing time and season variables. Set-ups of the experiments were similar to the one reported above by Harsha et al [56]. Here, researchers utilized light synthetic greywater mix to feed the two green wall systems. One daily standard dosing of 4 L of greywater mix was given to the systems in a time interval of 30 minutes (eq. 8 L/h) using a drip irrigation system. Synthetic greywater was fed into the system five days a week for a whole year. Furthermore, two high concentration events where pollutants were double - each of the duration of a single day - were experimented throughout the entire duration of the study. Finally, eight water quality sample events occurred during the experiment to assess pollutants removal efficiency with regards to COD, TN, ammonium, oxidized nitrogen, TP, filterable reactive phosphorus (FRP), total dissolved phosphorus (TDP), total dissolved nitrogen (TDN), dissolved organic nitrogen (DON), and TSS. Furthermore, to assess water quality, E. coli, water color, electrical conductivity (EC), and pH were sparely analyzed.

Tab. 7: Experiment set-ups

System	Dimensions	Media mix	Media quantity	Inflow	Irrigation
Pot design	150 mm depth each pot 450 mm total height	1/2 Perlite 1/2 Coco coir	6 L each pot 18 L total	4 L/d in 30 min time	Drip irrigation system
Block design	450 mm height 230 mm diameter	1/2 Perlite 1/2 Coco coir	6 L each pot 18 L total	4 L/d in 30 min time	Drip irrigation system

The data concerning the efficacy of the greywater treatment were calculated as the percentage difference between pollutants concentration in inflow and outflow water. Both systems proved to perform well following high pollutants concentration events, resulting in no appreciable differences between pot a block design, indicating that both systems can tolerate unpredictable picks in pollutants concentration in inflow water. Nonetheless, in these extremes circumstances, vegetated systems in both designs performed better than non-vegetated ones, confirming that plants add an important role to the sole microbial removal process played by the media. Plants' growth and maturation did not affect TSS and COD removal, but play a crucial role in TP and FRP removal, as shown in Table 8. In this regard, vegetated systems showed a higher performance compared to the non-vegetated ones. Furthermore, TP removals increased over time in vegetated blocks in comparison to vegetated pots, which, in contrast, showed a higher rate in the first sampling collection events. Nonetheless, the increased removal performances of both vegetated and non-vegetated configurations in both systems indicate that microbial processes become more effective over time rather than plant nutrient uptake.

Tab. 8: Comparative pollution performance results of all green wall designs across 4 sampling events. Results here are expressed as percentage of the median value

Pollutant	N-Pot	V-Pot	N-Block	V-Block
TSS	97	98	98	99
COD	91	94	91	92
TN	82	92	85	92
DON	88	92	91	94
TP	**23**	46	**30**	40
FRP	**21**	44	**22**	35
Characteristics	**N-Pot**	**V-Pot**	**N-Block**	**V-Block**
COLOR	82	83	81	83
EC	-16	3	11	21
pH	-	-	-	-
TURBIDITY	98	98	98	98

Regarding water characteristics, pH wasn't affected by non of the systems, with all the outflows ranging from 6.5 to 7.4 remaining within recommended pH limits for optimal plant growth, for the duration of the experiment. EC increased much more in block design compared to pot design, nonetheless, salinity level remained consistently below the recommended values for treated greywater reused based on US EPA (2012) (<700 μS/cm). Color removal performances were high in both vegetated and non-vegetated designs, due to the high removal of TSS provided by the media soil.

Finally, this study concluded that both pot and block design consistently reduce pollutants content in grey water and are usable systems for on-site greywater treatments. Both systems comply with national and international reuse guidelines [65, 66, 67] TSS (<10 mg/L), turbidity (<5 NTU), and COD (<10 mg/L BOD which converts to ~ < 35 mg/L COD), but they would require further disinfection for E. coli compliance for unrestricted reuse [P]. The only appreciable difference concerned TP and FRP removal, where vegetated pots have shown higher performances. As a conclusion, the study affirmed that ultimately, however very similar in terms of performances, between pot design and block design, the former would be recommendable due to practical advantages (e.g., ease of maintenance and odor control).

S2: Dimensions of the pot design green wall

The second study analyzed pollutant distributions among the three levels of the green wall only in the pot design configuration. The objective was to test the pollutants removal capacity at each level of the system, assessing the optimal height of pot design for proper greywater treatment. The set-ups were exactly the same as S1 for pot design, using five vegetated and four non-vegetated configurations and the same light synthetic greywater mix. Here, species-specific plants' nutrient absorption rates were analyzed similarly to the first reported study by Harsha et al. (2017) [56]. Utilized plants are shown in Table 9.

Tab. 9: Plants analyzed in S2 in green wall pot design

	Hight pollutants uptake	**Low pollutants uptake**
Vegetation type	*Carex appressa*	*Ophiopogon japonicus*
	Nephrolepis obliterata	
	Liriope muscar	

The study was conducted for three days during the second week of the last month of the whole experiment. This way, researchers could analyze different pollutant removals when plants were completely mature. This study was then divided into:

- Day 1: Collection of effluents from the top level, using 1 L sample and use the remaining outflow to irrigate the second level plant.
- Day 2: Collection and sampling of the whole effluent quantity from level two (middle level).
- Day 3: Complete collection of the effluent from the bottom level.

Same as for the S1, water samples were analyzed for TSS, TN, ammonium, oxidized nitrogen, TDN, TP, FRP, COD, E. coli, EC, pH, turbidity, and apparent and true color. The results were presented by the researchers as average outflow concentrations across all the configurations of pot design. The analysis of treated greywater in S2 showed different impacts of plant species on pollutants removal on each level. It was noticed how the top level, which received the direct greywater inflow from the tap, showed the greatest pollutants removal. TSS and COD achieved high removal rates already at the top level, reaching a statistically significant reduction also in the middle level and just a very slight reduction at the bottom level, suggesting that the system already reached its absorption limit after the first two levels. Phosphorus, expressed in TP and FRP, was only absorbed in the top level, while the middle and the bottom levels played no significant role in P removal. On the other hand, Nitrogen removal was directly affected by the plant species, with *C appressa* and *N. obliterata* showing the best performances for TN and ammonium removal, and occurred throughout all three levels. The E. coli removal was evident only in the first level, with insignificant reduction rates across the middle and bottom levels. Concerning color, no differences were appreciated between vegetated and non-vegetated configurations, showing that the growing media is the main factor in color polishing. Nonetheless, each level tends to leach color to the next one, and particular care should be taken in configurations with more than three levels. The same happened with pH, which proportionally increased at each level. Concerning EC, it consistently increased at each level exhibiting lower values at the top. Only *N. obliterata* showed both no different pH and EC increase across the levels, being able to control salt accumulation across all the levels.

In conclusion, it appeared that a three levels pot design green wall was sufficiently efficient for the removal of most pollutants with all the used plant's species. Furthermore, the increased pH and

EC, as well as the worsening in water color suggests that adding more levels to this configuration would add more problems than benefits. Indeed, this study demonstrated that most nutrients (TP and TN) are captured at the top and middle level, causing growth problems due to P and N starvation to the plant at the bottom level. In this regard, it seems that shorter walls of only two levels (2x200 mm) would perform even better, with the advantages of being cheaper and easier to maintain. If a greater surface must be covered and a higher green wall is needed, multiple two-level designs could be stacked one on top of the other, with different inflow and outflow points. Finally, the selection of plant's species is important to assess overall performances. In this study, better performances were provided by *C. appressa* and *N. obliterata*, both providing high pollutants removal also in the one-level green wall. However, what emerged from this study is that most green wall plant species would assure efficient performances when utilized in two-level green walls.

Pathogens risk assessment associated in hydroponically grown crops with NBS treated greywater and urine-based fertilizer

Source-separation sanitation systems offer the possibility to separate greywater from black and yellow water, reducing to minimum the cross-contamination between the waste streams. As greywater is the less polluted of the streams, separating it at the source may reduce the contamination in terms of microbial pathogens, heavy metals, organic pollutants, components in pharmaceutical residues, and personal care products, which threaten the public's health when reused directly with insufficient treatment. However, greywater must receive appropriate treatment to be safely reused and be stripped from harms pathogens and bacterias. As previously reported, new studies demonstrated that the potential health threat can be reduced when proper greywater treatment are associated with hydroponic crops growth. Nonetheless, health risks are associated with treated wastewater reuse for vegetable production, as well as non-potable consumption depending on factors such as the quality of the treated wastewater, the irrigation method used, the time interval between irrigation–harvest–consumption, and producer and consumer habits. Indeed, greywater may contain various microbial pathogens and hazardous chemicals depending on the nature of the raw greywater and the treatment's efficiency. Hence, if not properly treated, irrigating crops with greywater may result in the accumulation of heavy metals and the contamination of the crops with microbial pathogens which may cause [4].

Irrigation with wastewater for vegetables and food crops may result in the bioaccumulation of heavy metals, and, at the same time, it may cause the contamination of plant products with microbial pathogens. Various health problems can occur and develop due to the consumption of contaminated vegetables and the consumption of food contaminated with heavy metals, and this may cause the disruption of various biological processes in the body, leading to a decreased immunological defense, growth retardation, disability associated with malnutrition, and cardiovascular, neurological, kidney, and bone diseases [14,15].

In this regard, a recent study by Eregno et al. (2017) [4] assessed the quantitative microbial risk assessment (QMRA) models and chemical health risk assessment (CHRA) of hydroponic growth lettuce with greywater irrigation and diluted urine as nutrient solution. Concerning the presence of E.coli, lettuce treated with urine and greywater presented a significant reduction of E. coli. Indeed, no E. coli were observed in any of the plant samples collected from each of the treatment plots [4]. The results of this study point out that the greywater treatment system efficiently removed E. coli. Thus, the integrated hydroponic system has produced lettuce without exceeding target risk thresholds [4]. Considering the QMRA, it was studies with regards to the concentrations of sample pathogens like Cryptosporidium, Campylobacter, and Norovirus. The study concluded that the infection risk was very low, also due to the minimum exposure of the lettuce to irrigation water. respectively. The health risk of both lettuce consumption and production activities based on the corresponding assumptions and scenarios were below World Health Organization (WHO) health-based targets [67]. Concerning the chemical risk due to lettuce consumption, the concentration of heavy metals in the plants was expressed in terms of a health risk index (HRI) and targeted hazard quotient (THQ). Arsenic (As) and Chromium (Cr) were considered the major risk contributor to lettuce consumption, whereas Cadmium (Cd) was considered the lower. However, the index of all three elements were below the critical value. Hence, this study demonstrated that the concentration of heavy metal and harmful pathogens in hydroponically grown lettuce treated with urine and greywater does not represent a threat for human consumption. However, it was noted that heavy metal accumulation varies substantially among the different species of lettuce that were grown [4]. Thus, it is recommended to assess the content of heavy metals and pathogens beforehand, through field experiments, when proposing different crops for BIA projects that intend to use urine and greywater as nutrient solution. The results of this study are encouraging, but more data concerning the safe consumption of urban crops grown with wastewater is necessary.

3. Conclusions: design inputs for complete nutrient and water recovery in Building-integrated agriculture projects

As demonstrated by the analysis of the case studies reported in this research, and from an extensive literature review, water reuse may provide a potential nutrient source for urban agriculture. Moreover, it is possible to further associate hydroponic systems with domestic wastewater treatment to reach high discharge standards. This way, minerals contained in urban wastewater can provide crops with natural fertilizer, eliminating dangerous environmental runoffs. Treated domestic wastewater from urban waste-streams contains, in fact, nitrogen, phosphorus, and potassium among other nutrients.

The mineral composition amounts may vary depending both on the quality of the wastewater and the level (or technology) of the treatment. In this sense, reusing domestic wastewater can be a valuable solution to reduce the environmental impact caused by the application of mineral fertilizer in agriculture. However, limitations to the application of treated wastewater reuse as fertilizer for UA in urban areas consist of social acceptability and health concerns regarding the presence of pathogens and heavy metal in the treated wastewater. A document produced by the EU water directors regarding the guidelines for wastewater reuse in Europe found out that social acceptance towards treated wastewater varies between individual Member States [68], and highly depends on the crop purpose and how crops are consumed. One way to address the issue of social acceptance of treated wastewater used as fertilizer would be developing educational and communication strategies that can ensure and reassure the population on the safety of specific wastewater treatment processes for the environment and general health.

Thus, due to the potential interaction with the general public, wastewater treatments require special attention in all aspects of communication, awareness and participation, as well as effective water quality monitoring and control [68]. For this reason, the European Union has developed specific reuse guidelines within the WFD (Water Framework Directive 2000/60/EC) and a specific directive concerning urban wastewater treatment (Directive 91/271/EEC). European wastewater reuse guidelines are important to ensure the safe water reuse. To do so, it is important not only to apply water quality standards appropriate to the specific use, but also to ensure adequate and reliable operation of water reuse systems and appropriate regulatory enforcement. Until now, European guidelines have served as operational guidance to avoid unwanted health and environmental consequences connected to wastewater reuse, and they do not recommend any chemical, microbiological, and physical standards. In this sense, some Member States (Cyprus, France, Greece, Italy, Portugal and Spain) have developed and adopted water reuse standards in their legislation. Only very recently, the European Union has developed a new regulation draft on minimum requirements for water reuse [69]. The new rules will apply from 26 June 2023 and are expected to stimulate and facilitate water reuse in the EU. Only very recently, the European Union has developed a new regulation draft on minimum requirements for urban wastewater reuse for agricultural irrigation, in accordance with the guidelines set out by the previously cited Directive 91/271/EEC [68]. The new rules will apply from 26 June 2023 and are expected to stimulate and facilitate water reuse in the EU. They have been developed in the framework of the New Circular Economy action plan [70] adopted in 2020. As it reads in the European Commission [69] website in the “Environment” section, the new Regulation set outs [https://ec.europa.eu/environment/water/reuse.htm]:

- Harmonized minimum water quality requirements for the safe reuse of treated urban wastewater in agricultural irrigation;
- Harmonized minimum monitoring requirements, notably the frequency of monitoring for each quality parameter, and validation monitoring requirements;
- Risk management provisions to assess and address potential additional health risks and possible environmental risks;
- Permitting requirements;
- Provisions on transparency, whereby key information about any water reuse project is made available to the public.

In this context, minimum requirements applicable to reclaimed water intended for agricultural irrigation have been divided into three classes as reported in Table 10a and 10b. Crops belonging to a given category shall be irrigated with reclaimed water of the corresponding minimum reclaimed water quality class.

Tab. 10a: Classes of reclaimed water quality and permitted agricultural use and irrigation method

Minimum reclaimed water quality class	**Crop category**	**Irrigation method**
A	All food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw	All irrigation methods
B	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	All irrigation methods
C	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	Drip irrigation or other irrigation method that avoids direct contact with the edible part of the crop
D	Industrial, energy and seeded crops	All irrigation methods

Source: *REGULATION (EU) 2020/741 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 May 2020 on minimum requirements for water reuse [69]*

Tab. 10b: Standards required for reclaimed water usage

Reclaimed water quality class	Indicative technology target	E. coli (number/ 100 ml)	BOD (mg/l)	TSS (mg/l)	Turbidity (NTU)	Others
A	Secondary treatment, filtration, and disinfection	≤ 10	≤ 10	≤ 10	≤ 5	Legionella spp.: < 1 000 cfu/l where there is a risk of aerosolisation Intestinal nematodes (helminth eggs): ≤ 1 egg/l for irrigation of pastures or forage
B	Secondary treatment, and disinfection	≤ 100	In accordance with Directive 91/271/EEC	In accordance with Directive 91/271/EEC	-	
C	Secondary treatment, and disinfection	≤ 1000			-	
D	Secondary treatment, and disinfection	≤ 10 000			-	

Source: *REGULATION (EU) 2020/741 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 May 2020 on minimum requirements for water reuse [69]*

Hydroponically cultivated crops belong to class A in the European classification, as they are constantly in contact with irrigation water and water drops may contaminate the skin or the leaves of the plants. In this regard, assessing the quality of source-separated waste streams is crucial to determine the removal efficacy of decentralized hydroponic wastewater systems. Indeed, the physical and chemical parameters of urine and greywater may vary depending on the location, local diets, and people's habits. Hence, the number of nutrients and pollutants in waste streams must be assessed beforehand and must be considered when assessing further fertigation requirements [69]. Thus, monitoring irrigation water quality and discharge parameters is crucial for the success of hydroponic wastewater treatment. Supply of reused water containing nutrients would have to ensure that the amount of pathogens is not harmful to the environment and that the water does not contain any other pollutants that put human health and the environment at risk [69].

Furthermore, the quantity of nutrients that can be recovered from urban domestic wastewater is a crucial factor in determining the efficacy of the production systems, affecting its feasibility in highly dense populated urban areas. The final part of this chapter will be dedicated to the analysis of the results presented in the analyzed case studies, specifically focusing on the efficiency of recovered nutrients and water with regards to hydroponic production.

These results, together with the sets of regulations provided by the EU, will serve as design inputs for the design of decentralized hydroponic wastewater treatment integrated into buildings.

3. 1 Efficacy of urine-based nutrient solutions in hydroponic production

In a previous section of this same Chapter, two explanatory case studies of nutrients recovery from urine were summarized and analyzed. The reported analysis focused on recovering technologies, comparing two state-of-the-art systems for complete or partial nutrients recovery from yellow water. Here, results in terms of discharge standards and plants growth are analyzed and will constitute design inputs for the development and the design of on-site wastewater treatment coupled with hydroponic.

Struvite precipitation + ammonia stripping

The first case study by Yang et al. (2019) [3] used struvite precipitation coupled with ammonia stripping to recover N, P and K. To test the efficacy of urine-based nutrient solution, researchers fed the crops (water spinach) with four different nutrient dilution ratios (1:10, 1:20, 1:30, 1:50), and compared results with plants grown with commercial fertilizer. Results showed that compared with the commercial nutrient solution, pretreated urine contained lower concentrations of many nutrition elements, however they were sufficient for plant growth [3]. Furthermore, plants fed with urine solutions at 1:20, 1:30, and 1:50 dilution ratios showed higher removal rates compared to commercial fertilizers, meaning that nutrients contained in urine are readily available for plants' absorption.

As reported in Table 11, nutrient solution with 1:50 dilution ratios showed better performances in Nitrogen and Potassium conversion rate, which is the main indicator of measuring the utilization efficiency [3], and, as such, was the most satisfying in terms of pollutants removal, consistently reaching Singapore and European discharge standards [3]. On the contrary, plants treated with commercial nutrient solution showed lower conversion rates, indicating that further treatment in required to remove nitrogen and potassium from the hydroponic wastewater.

Tab. 11: Nitrogen and potassium conversion rate of plants, and final pollutant removal efficiency in urine at different dilution ratios.

Parameter	**1:10**	**1:20**	**1:30**	**1:50**	**NS**	**Unit**
N	0,07	0,29	0,37	0,46	0,22	mg/mg
K	0,02	0,33	0,40	0,51	0,27	mg/mg
COD	66,3	65,0	63,1	58,1	NA	%
TSS	46,9	31,3	NA	NA	NA	%
TN	42,3	40,6	45,9	49,4	33,1	%

Source: *Yang et al. (2015) [2]*
Abbreviation: *NS - commercial Nutrient Solution; NA - Not available or statistically insignificant*

Plants' growth performances were assessed by analyzing different parameters such as Plant Growth Rate (PGR) and Plant Leaf Number (PLF). Maximum PGR and PLN occurred when urine had was at 1:50 dilution ratio. These results were comparable with PGR and PLN occurred when using the commercial nutrient solution. Also, Shoot Dry Mass (SDM), Plant Water Content (PWC), and Root Dry Mass (RDM) had similar values in plants treated with 1:50 urine dilution ratios and commercial fertilizers. Furthermore, plants at 1:50 dilution ratios showed a better and greener color compared to plants treated with lesser dilution ratios. Concerning nutrients, N, P, and K are the essential nutrients for plant growth and are highly present in urine. In comparison with plants treated with urine-based fertilizer, plants in the commercial nutrient solution presented the highest N and P content, which could be attributed to the higher initial TN and TP concentration in the solution [3]. On the contrary, K content showed the opposite tendency since accumulation increased in higher dilution ratios. The study reported that this might be caused by salt-induced mineral perturbations as Na concentration decreased with increasing dilution ratios [3].

The results extrapolated from the analysis of this case studies indicate that the best dilution ratio for urine-based fertilizer is the 1:50 ratio. Plants treated with this dilution ration obtained optimal growing conditions, comparable to plants treated with commercial fertilizers. Furthermore, the hydroponic system achieved high removal rates of P (95%), N (92%), and COD (73%). The hydroponic system consisted of a tank of transparent PVC with 6 mm thickness and 800 mm length, 600 mm width, and 100 mm height. The tank was divided into three troughs. Each trough was covered with PVC material and provided with 5 holes for plants growth. Each trough had a volume of 5 L to ensure sufficient contact of plant roots within the medium.

Considering the characteristics of the system, the study concluded that the production capacity of 5L diluted urine (1:50) can support the growth of 45 small plants with a total dry mass of 1.65 g. However, the experiment indicated that to obtain such results, a high amount of water is required to dilute the nutrient solution. In this sense, treated greywater and/or rainwater are important resources to comply with the system requirements. Furthermore, cultivated plants should be tested for food safety, such as pathogens (e.g., Escherichia coli, Cyclospora, Listera monocytogenes, and Salmonella enteritis), heavy metal, and micropollutant accumulations to be commercialized in urban environments [3].

System requirements and expected results are summarized in Table 12 and further discussed in the following technical sheets.

Tab. 12: Struvite precipitation + ammonia stripping system's components for wastewater treatment integrated with hydroponic production

Component of the system	**Function**	**Characteristics**	**Operational requirements**
Urine diversion toilets (UDTs)	Separate urine from feces	Depending on the typology.	Installation in buildings
Stabilization tank	Stabilize urine and add urease enzyme to enhance urea hydrolysis	Sizes depend on the quality of collected water. Tanks should be water and odor-tight	Stabilization depends on the retention time of urine in the tank. Longer periods could guarantee better pathogen performances, but will enhance malodor in urban areas.
	Odor mitigation		
Struvite reactor	Recover phosphate and ammonia from fresh hydrolyzed urine	Struvite precipitation can be done in the same stabilization tank or using another reactor.	Magnesium is added into the reactor to enhance chemical processes.
		A filter is required to separate solids from treated urine	Mixing processes happen in the reactor. Reaction time and optimal doses of Mg are studied in laboratory
			Effluent from the reactors must be filtered. Dimensions of the filters depend on the effluent
Stripping reactor	Remove ammonia and nitrogen from stripping effluent	Design characteristics of the reactor may vary.	The liquid mixture is contacted with air within a reactor to remove the volatile components by mass transfer from the liquid gas phase.

Tab. 12: Expected results of urine-based fertilizer for hydroponic wastewater treatment

Outcome	Parameters	1:50 dilution	Commercial fertilizer	European Union standards	Unit
Hydroponic crop production (water spinach)	PRG	0.68 +/- 0.07	0.84 +/- 0.04	-	cm/d
	PLN	2.27 +/- 0.28	2.37 +/- 0.31	-	pieces/d
	SDM	0.33	0.38	-	grams
	RDM	0.05	0.05	-	grams
	PDM	0.38	0.43		grams
	PWC	94	94.5	-	%
Discharge standards	pH	5.31	-	NA	
	COD	35	-	125	mg/L
	TSS	10	-	35	mg/L
	TN	12.6	-	15	mg/L
	NO_3-N	2.1	-	NA	mg/L
	TP	0.3	-	1	mg/L

In conclusion, the combination of struvite precipitation, ammonia air stripping, and hydroponic production produced promising results with regards to plants' growth, achieving high discharge standards even for more stringent EU requirements. However, pathogenic contents in edible plants must be assessed and further research is needed.

When integrated in building compounds and small district design inputs must take into consideration that:

- High dilution ratios (1:50) provide better performance, but they require a higher water demand.
- Struvite precipitation reactor can be integrated in buildings and compounds, but its dimensions depend on the inflow quantity. In high densely populated urban areas a unique plant may be more efficient especially when combined with air stripping reactors.
- Air stripping reactors provide better performances when they work with higher inflow quantity. In buildings or even compounds it is not recommendable to use small reactors as their efficiency will be affected.
- Pathogenic contents in treated urine may be a limitation to the production of edible crops in urban areas.

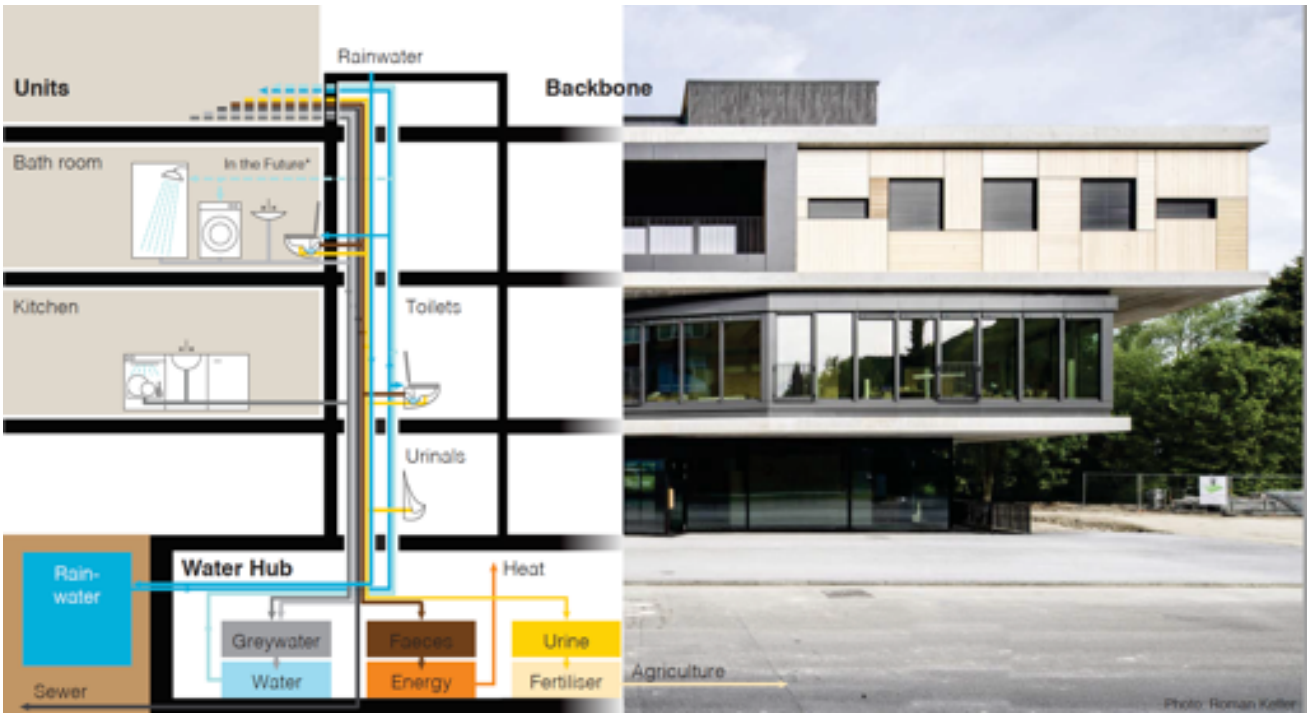
Nitrification + distillation

This technology was developed in the framework of the project VUNA (Valorization of Urine Nutrients for Africa) but was implemented by the EWAG research institute in Switzerland where it was also applied to recover nutrients from the Eawag's main building, Forum Chriesbach, and in the new NEST building (Fig. 9). The concentrated solution extrapolated from the nitrification process was then marketed in form of commercial fertilizer (AURIN) and then sold. The fertilizers

have been approved by the Federal Office for Agriculture for the fertilization of edible plants", and have been in use since February 2016. AURIN is a liquid fertilizer that is supposed to contain all the necessary micronutrients needed for plant growth (N, P, K) as well as several micronutrients such as iron, zinc, and boron.
The overall system consists of the following components briefly described below and that will be further discussed in the annexed technical sheets:

- *Urine storage tank:* Attenuates fluctuations and ensures complete urea hydrolysis.
- *Nitrification column:* An aerated tank containing the nitrifying bacteria mainly on biomass carriers.
- *Intermediate storage tank:* Stores the (partially) nitrified urine before it is distilled.
- *Vacuum distiller:* Concentrates the urine and separates distilled water.
- *Final product storage and recycling:* holds the concentrated nutrient solution and/or distilled water or recycles the water.

Fig. 9: Implementation of nitrification processes for nutrients recovery at the Eawag's main building (SW)



Source: *Etter B., Udert k., (2018) Nutrient & Water recovery from urine. A technology takes off*

When integrating hydroponics as final water treatment the last two processes (distillation and final product storage) may be avoided by recirculating the nutrient solution directly in the food production system. However, the distillation process contributes to removing harmful pathogens from the wastewater, other than reducing the volume of the nitrified urine by 97% into a concentrate nutrient solution. Therefore, pasteurization processes must occur in case the distillation phase is omitted.

The VUNA project replicated the recovery process twice in South Africa once at the Newlands-Mashu Field Test Site and once at the eThekwini Prior Road Customer Care Centre. Results regarding the efficacy of the concentrated nutrient solution applied to tomatoes' growth into a hydroponic system were reported by Shirly Tentile et al. (2020) [71] in a recently published article. In this experiment, nitrified urine concentrate (NUC) was given to tomato plants within a hydroponic system through fertigation using a drip irrigation system. Plants were cultivated both with NUC and typical commercial fertilizer. Final growth parameters were compared to assess the efficacy of the diluted NUC compared to commercial fertilizer for hydroponic tomatoes growth. After storage and nitrification, the urine was concentrated 20 fold, nutrients content is reported below in Table 13.

Tab. 13: Comparison of urine based fertilizer with commercial hydroponic fertilizer mix (CHFM)

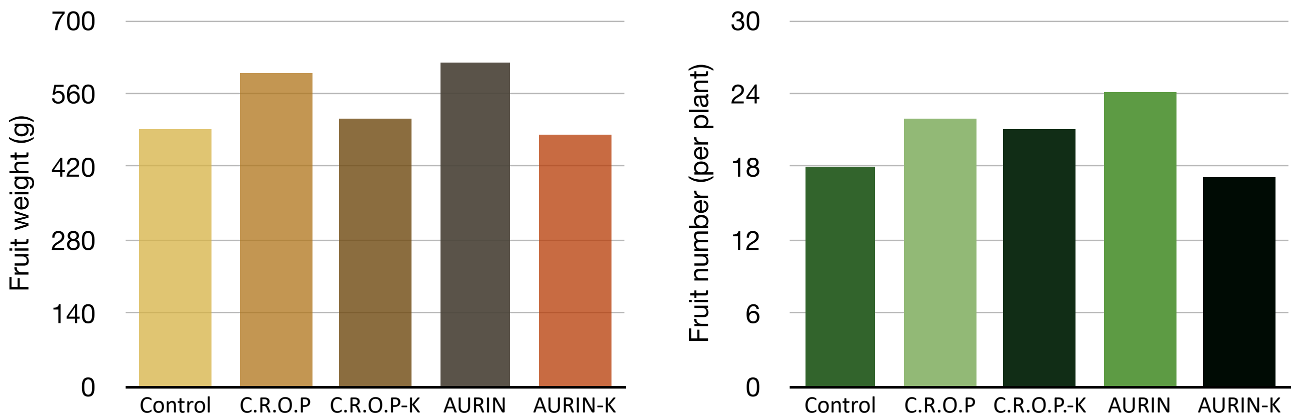
Parameter	NUC	CHFM	Units
TN	164.36±12.03	99.49±8.48	mg/L
P	8.81±1.53	26.04±3.20	mg/L
K	32.77±4.16	128.96±7.58	mg/L
Ca	0.33±0.03	102.92±7.28	mg/L
Mg	0.03±0.004	18.60±1.99	mg/L
Fe	0.013±0.003	0.775±0.1	mg/L
Mn	0.0003±6.5	0.186±0.03	mg/L
Zinc	0.004±0.0005	0.093±0.005	mg/L
COD	5226.00±296.98	-	mg/L
TSS	-	-	mg/L
pH	3.7±0.37	7.70±0.34	pH value
EC	2.68±0.14	3.83±0.15	dS/M
E. coli	-	-	cfu/100 mL

As expected, due to the nitrification process and the high content of nitrogen and ammonia in urine, TN concentration is higher in NUC fertilizer compared to CHFM. However, the ratio between P and N and K and N in urine-based fertilizers was found to be relatively lower compared to synthetic fertilizers. Nonetheless, the ionic form of both phosphorus and potassium makes it readily available for plant absorption upon application [71]. Chemical fertilizer and NUC fertilizer were given the same application rates to assess growth performances. As N is considered a limiting factor for plant growth, as well as the most dominant nutrient in urine, the nitrogen content in the NUC was used as determining factor for the nutrient content of the urine-based fertilizer.

Similar to the study conducted by Yang et al. (2015) [3], parameters such as SFM, shoot fresh mass; RFM, root fresh mass; SDM, shoot dry mass; SD, stem diameter; RDM, root dry mass; LAI, leaf area index, were considered to compare the efficacy of urine-based fertilizer on tomatoes' growth and yield compared to commercial fertilizer [71]. Results showed that there were significant differences in fruit mass, fruit number, harvest index, and yield across the treatments. The synthetic fertilizer showed the highest fruit mass, fruit number, and yield compared with NUC, which instead showed a better harvest index. Indeed, plant growth performance, physiology, and yield were significantly higher in plants treated with CHFM. However, this is probably since the commercial fertilizer recipe was specifically engineered to meet tomato requirements, while NUC fertilizer was not adjusted to meet crops demand. The high concentration of P and N in the NUC provided plants with high performances in terms of shoot dry matter, leaf area index, and chlorophyll content. However, the high content of N and the poor content of Ca might be the cause of the reduction in yield performances and low photosynthetic rate. Possibly, better growth and yields can be obtained with different dilution ratios (as also demonstrated by Yang et al.) where mineral nutrient concentration could increase at a slower rate than dry matter accumulation. Finally, the concentration of bacteria and pathogens in tomato fruits was analyzed after being harvested with regards to aerobic mesophiles, total and fecal coliforms. Tomatoes treated with urine-based fertilizers showed a reduced frequency and population of bacteria in the fruits, and the safety of the product was comparable with commercial fertilizers.

Further research was conducted by the VUNA team in Europe, specifically assessing the efficacy of treated urine as fertilizer in hydroponic greenhouses. In the trials that have been conducted, urine-based fertilizer showed a very good performance on most crops. In an experiment conducted by M. Maurer in Berlin [72] on Tomatoes (*Solanuml ycopersicum*) five nutrient solution treatments were given to the plants: i) Commercial fertilizer for final comparison with the urine-based nutrient solution (Control); ii) a nitrified urine solution obtained by the nitrification of synthetic urine and further pasteurization (C.R.O.P.); iii) the same nitrified urine with the addition of potassium (C.R.O.P. - K); iv) AURIN fertilizer from the nitrification and distillation of source separated urine (AURIN); v) AURIN fertilizer with the addition of K (AURIN - K). Tomatoes were cultivated in a NFT hydroponic system and the nutrient solution was diluted accordingly to plants' requirements. Treatments were compared regarding yield, mineral nutrition, and plant-morphological and plant-physiological parameters [72]. Differently from the South African experiment, when urine-based fertilizer was diluted accordingly to plants' needs, no significant differences in yields were found in crops traded with nitrified urine or commercial fertilizer, as shown in the chart below (Fig 10).

Fig. 10: Least square means of total fruit weight per plant and fruit number per plant



In conclusion, nitrified urine concentrate coming from treated urban yellow water seems to be a promising fertilizer for plants grown in hydroponic. However, a combination of urine-based and synthetic fertilizer could guarantee optimal growth performances, appearing the most promising solution at this time. The integration of lower doses of synthetic fertilizer may help the plants absorbing all the micro-nutrients they need to maximize yields. Furthermore, special attention should be put in dosing and preparing the nutrient solution, so to obtain the optimal dilution ratio for each specific crop. Besides, it has been reported that the application of nitrified urine as fertilizer may provide higher yields on larger-scale production. However, due to the limited space of urban production surfaces, it is difficult to expect maximum yields in urban areas.

Finally, discharge standards were met by the hydroponic effluent water [72], similar to what was shown in the research proposed by Yang et al. [2]. Total and fecal coliform, E.coli, and other bacterias were found in insignificant amounts in plants' fruits, making them safe for humans to eat.

3.2 Efficacy of green wall systems for on-site greywater treatments and limitations to their application

Considering the analysis of the two reported case-studies, with the addition of further results reported in the scientific literature [58], it is possible to affirm that NBS greywater treatment applications have high removal performances, indicating the suitability of green wall systems in treating domestic greywater. However, the efficacy of green walls with regards to greywater treatments may vary depending on the selected species of plants, the substratum in which they are cultivated, and the amount of hydraulic loading rate (HLR). Indeed, the cited experiments found different results based on the different set-ups choices. In particular, HLR does not only affect pollutants removal efficacy, but it is also a fundamental parameter to assess the final dimension of the green wall for greywater treatment. One of the limitations to the application of these systems for greywater treatment is, in fact, the lack of sizing guidelines able to assess the amount of GW that can be fed and efficiently treated by a specific system [58].

Hence, the identification of optimal design parameters for green walls and green roofs is essential to ensure high pollutant removal and efficient use of space [58]. In this sense, higher values of HLR are recommended in the design of green walls as they can receive larger amounts of greywater, providing a lower spatial footprint. Unfortunately, it has been demonstrated in these studies that higher values of HLR increase the velocity of filtration [58], limiting the retention rate, thus, reducing the contact time between the microbes located in the media, the plants' roots, and the flowing greywater. In this sense, excessive HLR may reduce pollutant removals. Nonetheless, the study conducted by Boano et al. (2020) [58], which compared 10 different experiments, found out that optimal performances in terms of HLR can be found up to the limit value of 500 L/sm/day. Specifically, BOD, COD, and TSS removal were less affected by higher HLR than TP and TN removal, which mostly depends on the type of the plants and on the media chosen.

Plants like *C. appressa*, *Canna lilies* and *L. japonica,* and *N. obliterata* showed the best performances in terms of pollutant removals and proved themselves resilient to operational and temperature variations. However, another limitation concerning the application of green walls for greywater treatment is the lack of information regarding the durability of the system. Issues connected to system clogging and long-term pollutants removal efficacy are yet to be addressed. Further field research and pilot applications must be conducted to assess the actual resiliency of this system with regards to greywater treatment. Nonetheless, the implementation of natural systems for greywater treatment and water reuse in urban areas can dramatically reduce fresh water usage in buildings [58], and real-life applications are a chance to improve social acceptance of treated greywater. A European study [73] concerning wastewater reuse in EU analyzed current social impacts and noted that the perception revealed by the European survey is that, in the view of some public administrations and of the population, treated wastewater still remains basically wastewater [73], even though it is widely known that in many urban and semi-urban areas in Europe surface or ground waters can have bacterial and chemical quality worse than that of a secondary-treated wastewater [73]. Therefore, the acceptance of water recycling is a crucial social factor, and the development of new projects that show to the public how recycled water can be used are fundamental toward a novel acceptance on the matter. Until now, the involvement of local NGOs and environmental associations proved to be, in some cases, a critical success factor [73]. The involvement of recognized associations radicalized in the territory helped building up credibility, trust and confidence in the local population. As that, recycled water projects may benefit by being accompanied by community education to demonstrate that the current technology is adequate to protect human health [73]. Once more, developing UA projects with on-site wastewater treatment need to be coupled with education activities and social involvement to increase social acceptance. A timely and active communication program to discuss the development processes and to discuss the risks and the measures in place to assure the safety of the water, may help to increase trust in the project [73].

Furthermore, developing high quality buildings using NBS wastewater treatment can be a powerful tool to change people's perspective with regards to wastewater reuse. In recent years it became clear how an effective architectural and aesthetic communication can influence people's opinion and acceptance on new technology (i.e. The Vertical Forrest by S. Boeri increased people's will to see green spaces integrated in urban buildings [74]). In this regard, the next chapter will further develop the application and the design guidelines of green walls for greywater treatment, and their possible application as attention catalyzer for the urban population.

3.3 Final discussion and supplementing material

As abundantly written in this chapter, closing the loop of nutrients and water in urban areas is now possible thanks to the application of on-site wastewater treatment technologies combined with source-separation sanitation systems. Improvements in wastewater discharge standards can be achieved by integrating a hydroponic system as tertiary wastewater treatment. Two main advantages can be encountered in doing so: i) Implement food production in urban areas limiting the use of chemical fertilizers; and ii) polish wastewater from dangerous runoffs, reaching high discharge standards.

The application of on-site wastewater technologies and hydroponic production systems is coherent with the new direction towards the idea of circular city planning that the studied municipalities of Amsterdam and London are taking. Integrating and coupling these two technologies can be a new path to follow for architects, planners, and municipalities for the development of new green buildings and urban districts. However, their application is still subject to field research and more pilot projects are necessary to improve the combination of these technologies, as well as increase the social acceptability of wastewater reuse. Uncertainties regarding the dimensions of green walls for greywater treatment and the durability of the system must be addressed, as well as the efficacy of greywater reuse as irrigation water for different hydroponic crops.

To better explain the practical applications of these technologies, supplement materials have been added at the end of this chapter. The supplement material consists of technical sheets and references to specific product developers to give an overall idea of the dimensions and costs of these systems, which are not specifically treated here but will be part of the discussion for the next and final chapter.

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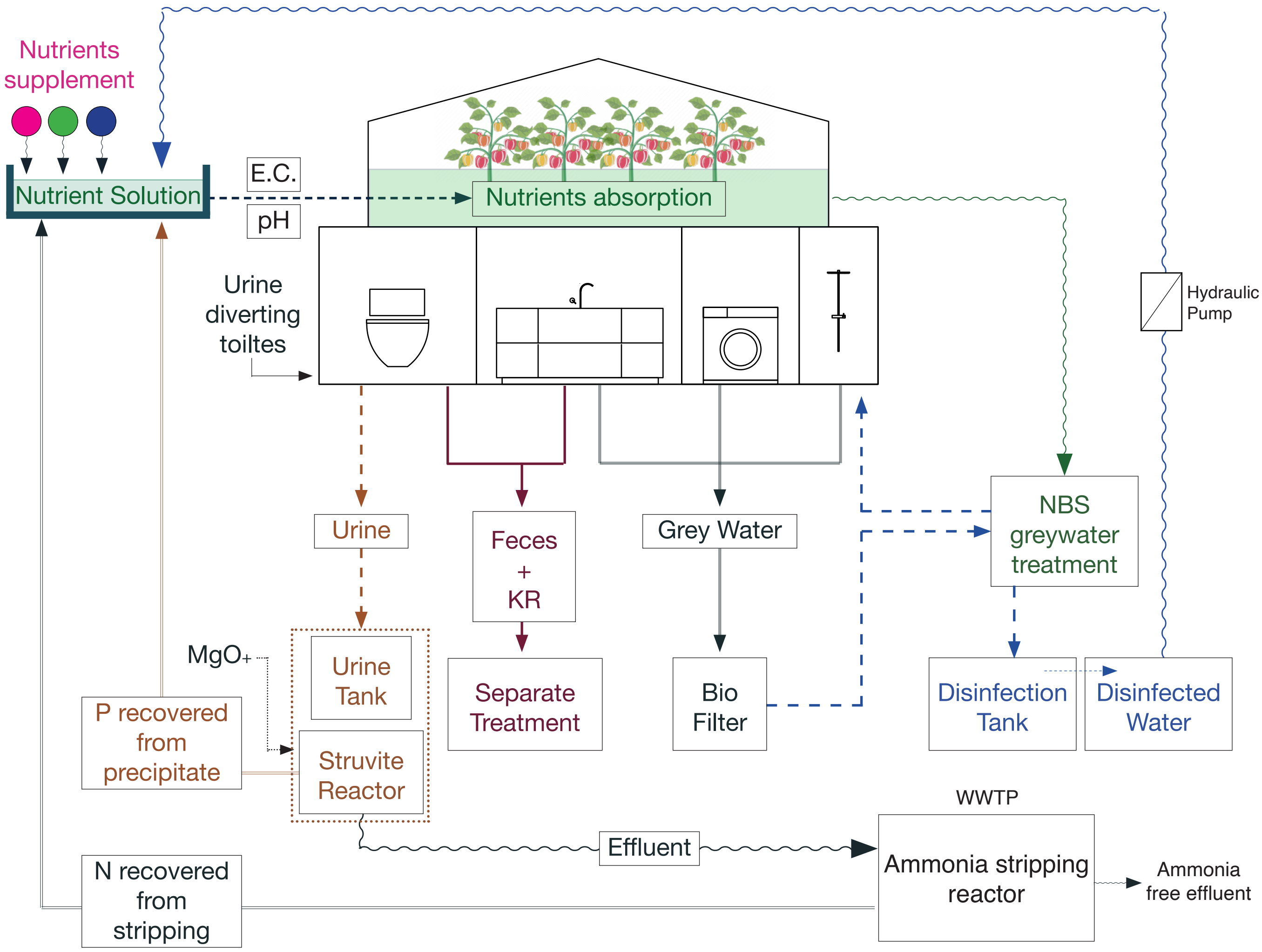
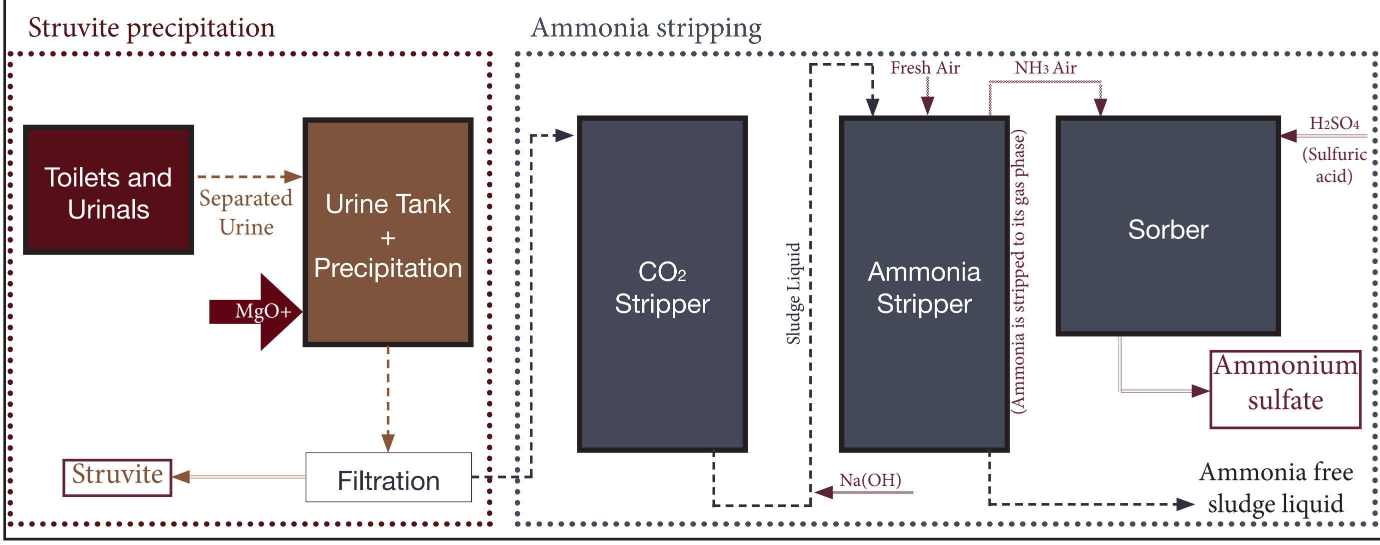
Supplementing Material

Hydroponic wastewater recovery concept with struvite precipitation	Sheet nr. 1

Based on the analysis of the operating methods and results of the experiment conducted by Yang et al., together with an extensive literature review concerning struvite precipitation reactor combined with ammonia stripping processes, it was possible to extrapolate the following design concept. This concept represents the expected flows of wastewater in a hypothetical building where recovered wastewater is used for plants' cultivation in the integrated hydroponic system. Further analysis on the inflow quantity and the estimation of masses dimension will be discussed in a site-specific case studied proposed in Chapter 5.



In this concept, struvite precipitation is operated within the building/compound (considering a max capacity of 100 people), while ammonia air stripping processes happen in a wastewater treatment plant. In case of new developments of entire districts, the ammonia stripping reactor could be planned within the development area, thus, limiting high special transportation costs. An example of the complete process of P and N recovery from struvite precipitation and ammonia stripping is reported below:



Urine diverting toilets

Sheet nr. 2

In high-income countries, urine separation has been proposed as a way of increasing the efficiency of centralized wastewater treatment plants. Thanks to source-separation obtained by urine diverting toilets less nitrogen would have to be removed in wastewater treatment plants.

Urine diverting flush toilets (UDFT)

The urine-diverting flush toilets most commonly used to date. It is similar in appearance to a conventional flush toilet, except for the diversion in the bowl. Urine is here separated from the faeces. The urine flows into a storage tank for further use or processing, while the faeces are flushed with water to be treated. The system requires dual plumbing, separating pipes for urine and brownwater.

Pipes should be installed with at least a 1% slope, and sharp angles (90°) should be avoided. A pipe diameter of 50 mm is sufficient for steep slopes and where maintenance is easy.

Advantages:
- Reuse of urine as fertilise
- Requires less water than a traditional flush toilet
- No real problems with odours if used correctly
- Looks like, and can be used almost like, a cistern flush toilet

Disadvantages:
- Limited availability; can not be built or repaired locally
- High capital and low to moderate operating costs
- Labour-intensive maintenance
- Requires training and acceptance to be used correctly
- Is prone to clogging and misuse
- Requires a constant source of water

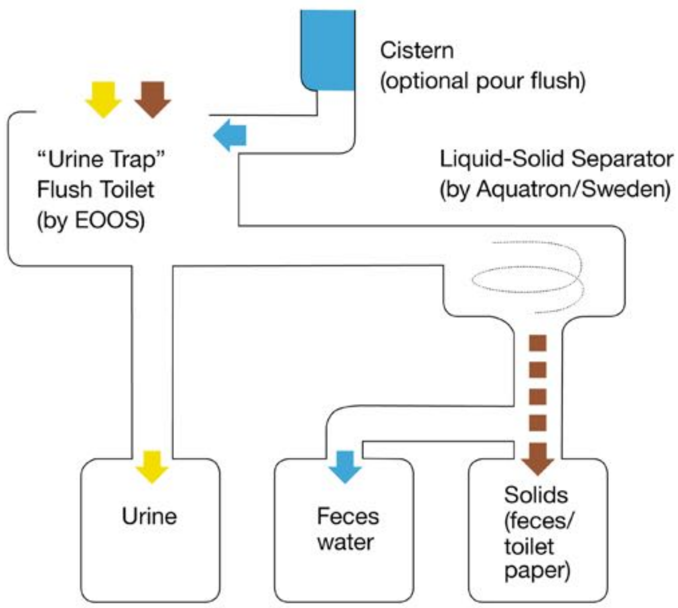
Utine diverting dry toilets (UDDT)

UDDTs are the most common type of source separation system; they are frequently installed at remote locations but increasingly also in urban settings. Solid and liquid wastes are separated by means of a sloping conveyor belt below the toilet seat, or by a partition in the toilet bowl. Here, the separation of waste streams is designed not only for urine collection but also to control odours and to facilitate composting of the relatively dry feces.

Pipes should be installed with at least a 1% slope, and a diameter of 50 mm is sufficient for steep slopes and where maintenance is easy.

Advantages:
- Does not require a constant source of water
- No real problems with odours and vectors (flies) if used and maintained correctly (i.e., kept dry) particles
- Can be built and repaired with locally available materials
- Low capital and operation costs

Disadvantages:
- Prefabricated models not available everywhere
- Requires training and acceptance to be used correctly
- Is prone to misuse and clogging with faeces
- The excreta pile is visible



Urine Trap by: EOOS
Online source: http://urinetrap.com/#

Example of UDFT
Source: https://sswm.info/factsheet/urine-diversion-flush-toilet

Urine storage tank	Sheet nr. 3

Urine storage tanks are most appropriate where there is a need for nutrients from fertilizer for agriculture. The urine storage tank should be appropriately sized to accommodate the number of users and the time required to sanitise the urine. It should be made out of plastic, fibreglass or even concrete.

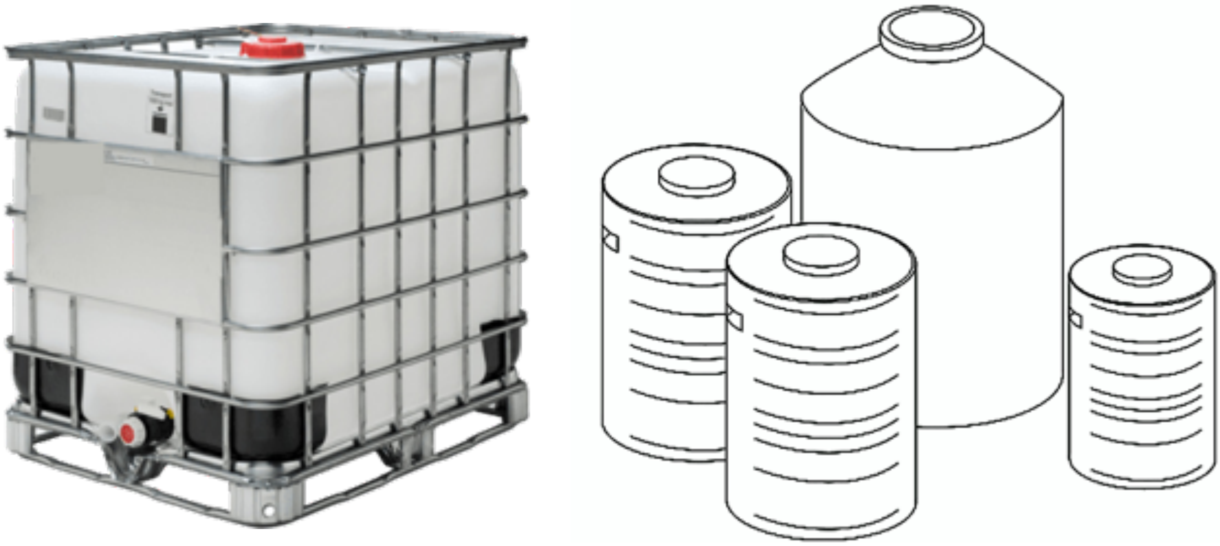
Example of urine collection tank at EWAG (CH)
Capacity: 1000 L

If the storage tank is directly connected with a pipe to the toilet or urinal, care should be taken to minimise the length of the pipe since precipitates will accumulate.

- Used pipes must have a steep slope (> 1% slope), no sharp angles, and large diameters (up to 110 mm for underground pipes).
- They should be easily accessible in case of blockages.
- It is important that neither the storage tank nor the collection pipe are ventilated, to avoid ammonia emissions and consequent malodors.

To minimise odours and nitrogen loss, the tank should be filled from the bottom. This means that the urine should flow down through a pipe and be released near the bottom of the tank. This will prevent the urine from spraying and avoid the backflow of air. Long-term storage is the best way to sanitise urine without the addition of chemicals or mechanical processes.

Example of different tanks' shapes



Urine storage tanks can be used in virtually every environment; tanks should be well-sealed to prevent leaks, infiltration and nitrogen loss. Urine storage tanks can be installed indoors, outdoors, above ground and below ground depending on the climate, space available, and soil.

Advantages

- Simple and robust technology
- Can be built and repaired with locally available
- materials
- Low risk of pathogen transmission
- Stored urine can be used as a fertilizer
- Small land area required

Disadvantages

- Mild to strong odour when opening and emptying tank
- Capital costs can be high (depending on the size and material of the tank)
- May require frequent emptying (depending on tank size)

Struvite precipitatotion reactor	Sheet nr. 4

Struvite precipitation is probably the best understood process for nutrient recovery from source-separated urine (Udert et al., 2015) as it has been widely tested proving to be technically feasible and economically beneficial. To precipitate the mineral struvite urine must be stored to satisfy all the requirements such as high pH value, high ammonia and phosphate concentrations. When the requirements are met, only a magnesium source has to be added to precipitate nearly all phosphate as struvite (Siciliano et al., 2020). Phosphate can be collected as struvite precipitate with minimum amounts of impurities. Indeed struvite is formed as a mineral salt that incorporates only low quantities of solids and that can be easily recovered by sedimentation (Siciliano et al., 2020). The development of reactors for precipitation and recovery has been at the centre of several studies in the past decades, however, two main reactor types are generally used and reported here below.

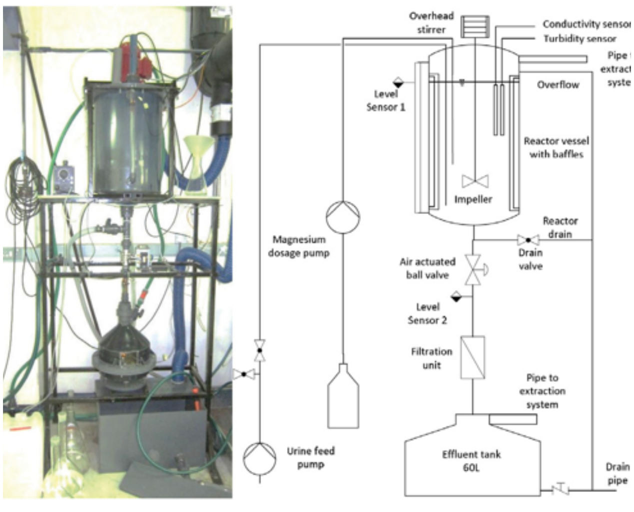
Stirred Tank Reactors—STR

STRs represent the most used reactors in laboratory studies (Siciliano et al.) as the control of struive formation is simpler compared to other technologies. These are very simple units equipped with a mixing system that allows for the homogenization of the wastewater with the reactants. Auxiliary devices for the introducion of reagents and the control of the operating parameters are needed. These reactors can operate continuously or in batch mode.

- A batch reactor works according to a series of phases and the struvite production and precipitation occur in the same unit.
- In a continuous reactor only the struvite formation takes place, while the precipitation phase occurs in a separate unit.

Advantages:
- Easy flow control.
- Can be used both in batch and continuos mode.
- Hydraulic reaction time can be reduced to a few minutes
- High peformances

Disadvantages:
- High stirring velocity requires relatively high energy inputs



Example of automated STR. Volume: 50 L
Source: *Grau, Maximilian & Rhoton, Sara & Brouckaert, Chris & Buckley, Christopher. (2015). Evaluation of an automated struvite reactor to recover phosphorus from source-separated urine collected at urine diversion toilets in eThekwini. Water SA. 41. 383. 10.4314/wsa.v41i3.10.*

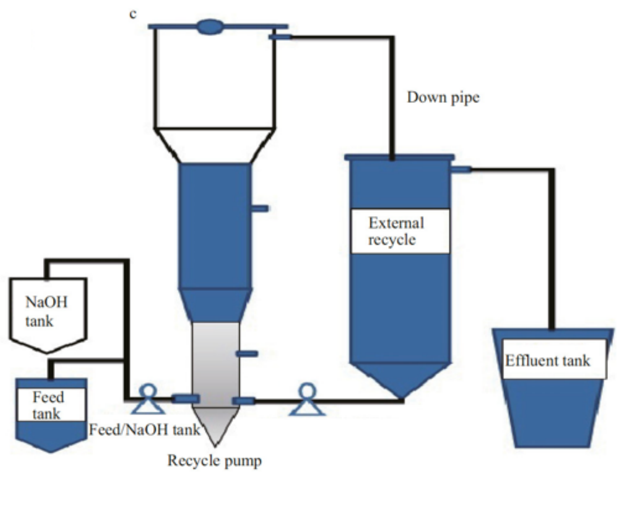
Fluidized Bed Reactors—FBR

The FBR consists of a central body with a predominantly longitudinal development in which phosphate crystals nucleation and growth take place (Siciliano et al.). The waste stream is introduced at the bottom together with the reagents necessary for struvite nucleation. From the top of the reactor, the liquid falls into an external clarifier from which part of the flow is recirculated to the bottom of the crystallization reactor

The recirculation flowrate can vary considerably depending on the type of wastewater and on the characteristics of the reactor. Different configurations and set-ups are found in literature for the optimization of FBRs. However, advantages and disadvantages may include:

Advantages:
- Rapid growth of struvite crystals
- Higher control on the dimentions of the phosphate particles

Disadvantages:
- High complexity management
- High flow rates that require high energy inuts
- Fluidization of solids produces erosion of the internal walls, hence high maintainance is required



Example of FBR. Feed tank: 60 L ; V. reactor: 9,5 L; h.: 1.1 m
Source: *Alemu, Awoke & Xia, Siqing & Jiang, Wei & Zhou, Lijie & Zhang, Zhiqiang & Hermanowicz, Slawomir & Xu, Xiaoyin & Shen, Shuang. (2014). Enhanced struvite recovery from wastewater using a novel cone-inserted fluidized bed reactor. Journal of Environmental Sciences. 26. 765-774. 10.1016/S1001-0742(13)60469-6.*

Ammonia stripping reactor

Sheet nr. 5

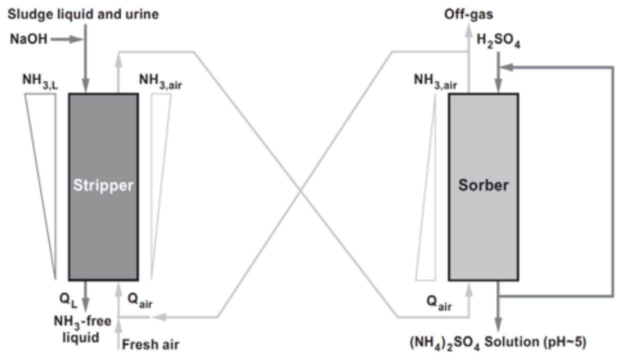
Ammonia can be removed from wastewaters through air stripping. Due to easy installation procedures and high ammonia removal efficiency, ammonia air strippers are widely used to remove ammonia from urine. Air stripping is a physicochemical process in which a liquid mixture is contacted with air to remove the volatile components by mass transfer from the liquid to the gas phase (Liu et al., 2014). The stripped ammonia is absorbed by a strong acidic solution such as sulfuric acid, forming mineral fertilizer for agricultural use. Between different technologies for stripping procedures, air stripping is considered the more suitable for decentralized reactors (Siegrist et al., 2013) . Here, first the ammonia is stripped to its gas phase, later NH3 is adsorbed in acid. Coupling air stripping with struvite precipitation improves the system performances preventing clogging issues as the phosphate has already been precipitated. Several reactors have been studied to assess the efficacy of air stripping from stored urine. Here, two main reactor concepts are briefly illustrated.

Stripping reactors with acid absorpion (Fig. 1)

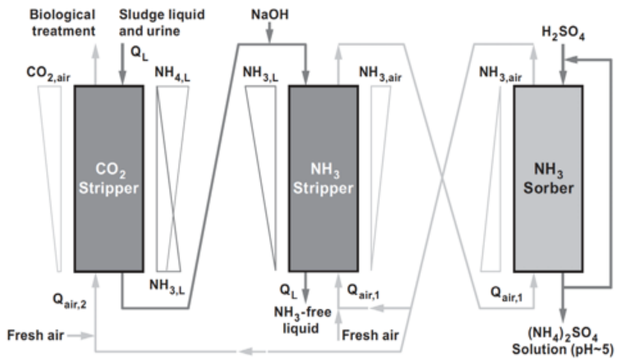
In this reactor, ammonia is recovered from urine by air stripping with consecutive ammonia adsorption in sulfuric acid. Here, packed columns, where a distributor is placed at the top, are used to increase the water/air interface. Columns' height and diameter depend on the water flow rates. In the digester, heated sodium hydroxide is dosed to shift the acid/base equilibrium towards ammonia. Thus, the air flowing out of the stripper is rich in NH3 and is transferred to the sorber column. Here, highly concentrated sulfuric acid is dosed to the sorber for ammonia adsorption. Ammonia is converted into ammonium in the sorber. The effluent is an ammonium sulfate solution with about 10% ammonia and a pH value of approximately 5 which can be used as fertilizer.

Air stripping with CO_2 pre-stripping (Fig. 2)

When using a CO_2 pre-stripping reactor sodium hydroxide dosage can be dramatically reduced. Since CO_2 is about one thousand times more volatile than ammonia, it can be stripped in the pre-stripper, which is operated with a significantly lower airflow than the ammonia stripper. Introducing fresh air to the air that is circulated between the stripper and sorber and introducing the off-gas to the pre-stripper additionally reduces the need for base addition (Siegrist et al., 2013). After the pre-stripping process, liquid and gas exchange between the stripper and the sorber follows the principle of conventional stripping reactors with acid absorption.The great advantage of the pre-stripping reactor is that ammonia and energy losses are minimal.



Flow scheme of air stripping with acid absorpion
Source: *H., Siegrist & Laureni, Michele & K.M., Udert. (2013). Transfer into the Gas Phase: Ammonia Stripping.*



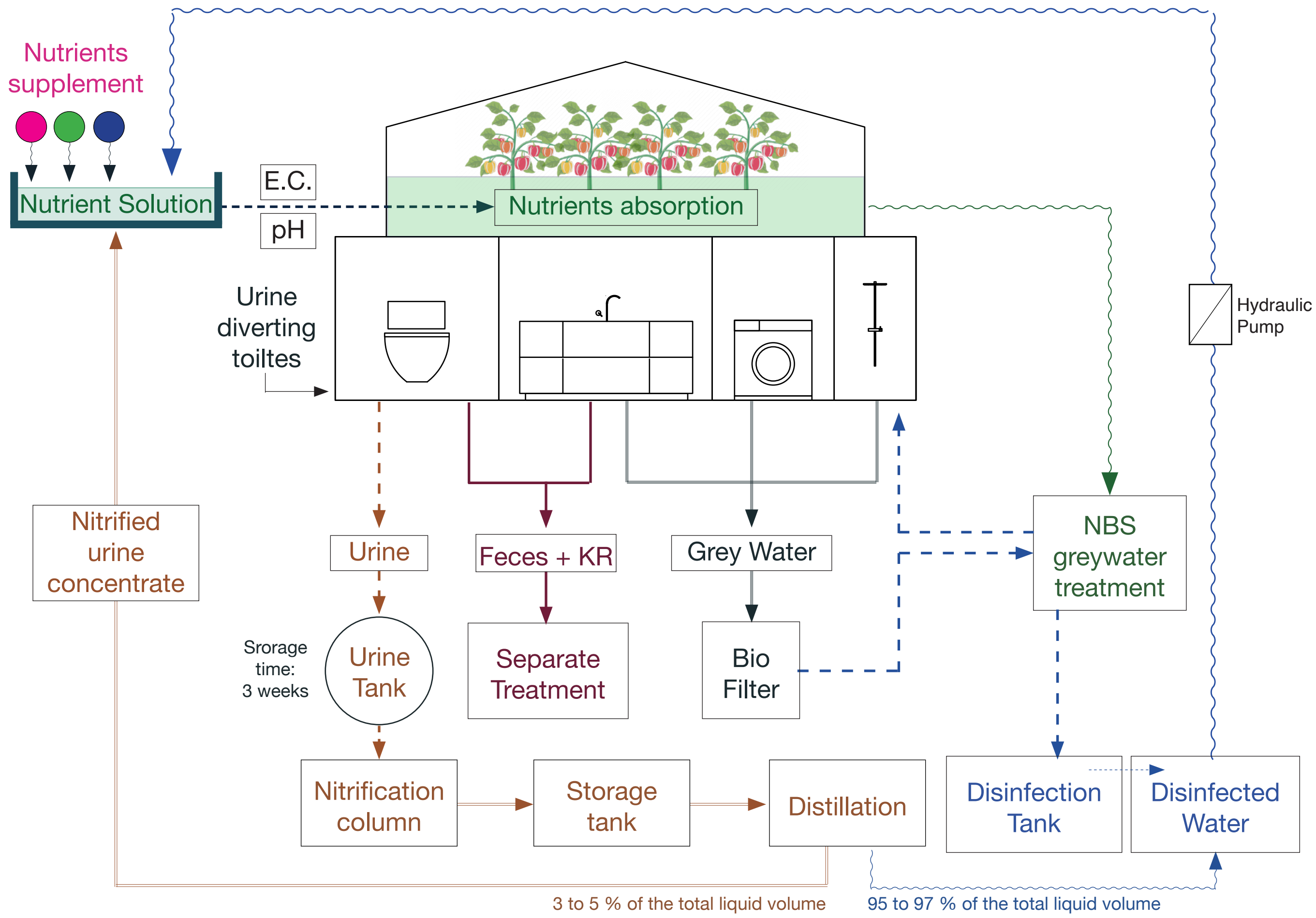
Flow scheme of air stripping with carbon dioxide pre-stripping
Source: *H., Siegrist & Laureni, Michele & K.M., Udert. (2013). Transfer into the Gas Phase: Ammonia Stripping.*

Example of packed columns in a CO_2 pre-stripping reactor
Site Location*: Natick, Massachusetts*

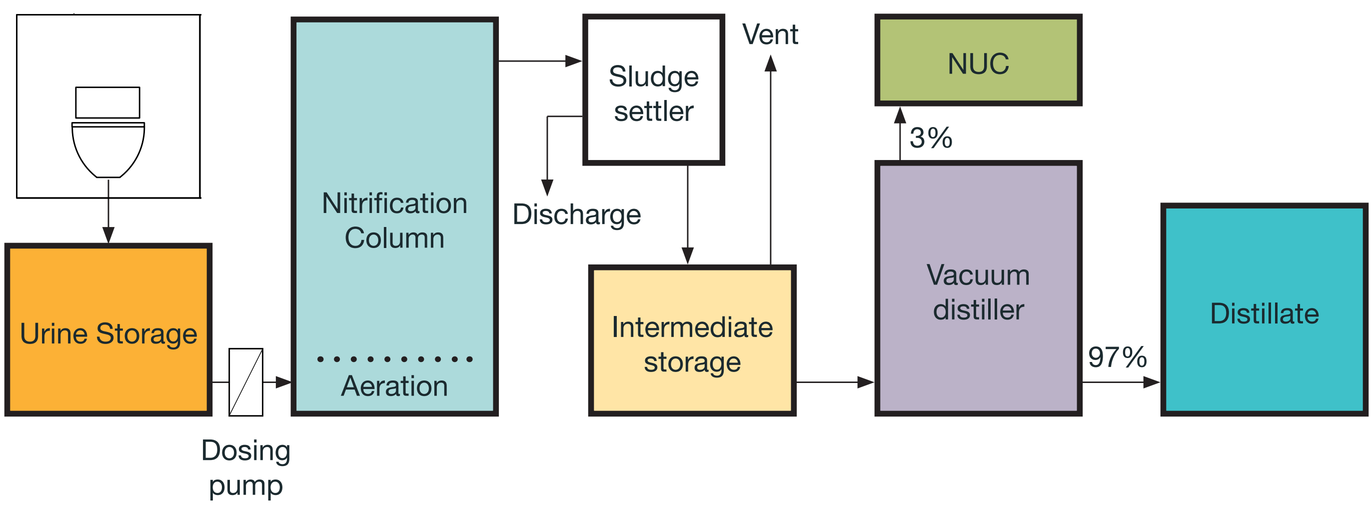
Container pilot plant by SUSTEC BV, THE NL
Pilot of struvite preciptiation in front of the stripping reactors

Hydroponic wastewater recovery concept with nitrification	Sheet nr. 6

Based on the analysis of the operating methods and results of the experiment conducted by the VUNA team in South Africa and in Switzerland it was possible to extrapolate the following design concept. Here, urine collected in the diverting toilets is collected in a storage tank. The storage tank's main task is to balance the flow so it was estimated that 3 weeks storage time should be provided. Later, urine flows in a moving-bed biofilm reactor MBR (sheet 7) that works as nitrification column. Here, urine is stabilized. The final treatment consists in distillation, where the effluent is concentred in a liquid solution, with a reduction in volume of aproximately 95%. The distilled water can be reused for non portable activities like flushing and irrigation.



In this concept, the complete nutrient recovery process obtained by nitrification is considered for a building/ compound of a max capacity of 100 people. The whole process could take place in the basement of a new building, or integrated in building renovation in case sanitation and piping would be renovated. The minimum space to accomodate the whole installations is 10 square meters.



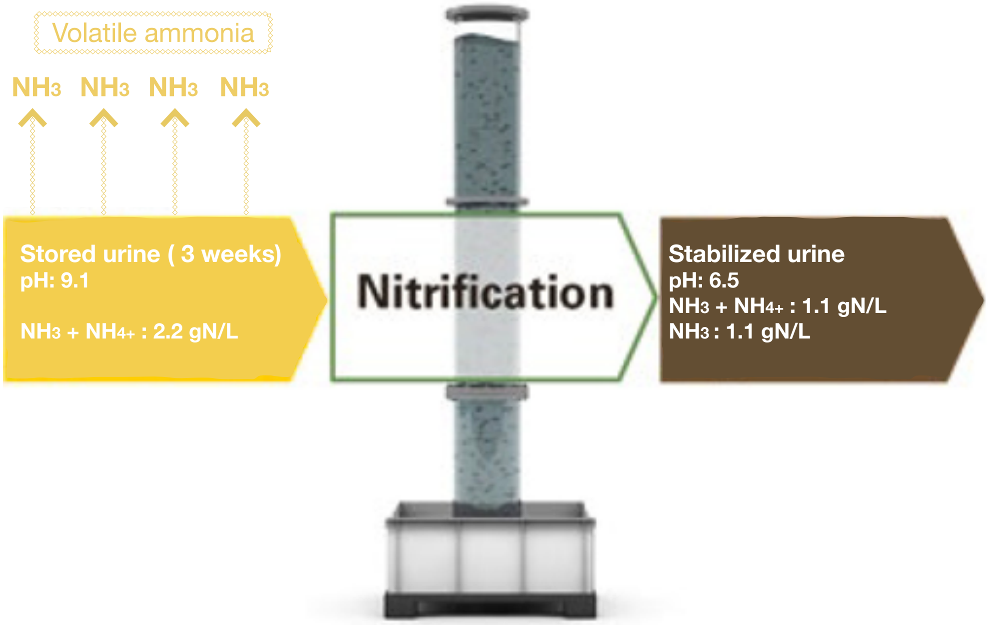
Nitrification column	Sheet nr. 7

The nitrificatio column is an aerated tank containing the nitrifying bacteria, mostly biomass carriers. For the costruction of the reactor plastic material like PVC, PP, PE are usually used. In the VUNA esperiment, the column of the reactor was filled with biomass carrier to form a Moving-bed Biofilm Reactor (MBR).

Polyethylene biomass carrier used in the MBR

Moving-bed Biofilm Reactor (MBR) design

The volume of the nitrification reactor has to be calculated based on the average ammonium concentration in the stored urine and the maximum nitrification rate. The ractor has a **maximum nitrification rate that varies from 400 to 800 mg/L/day.** Hence, in the VUNA reactor, as the ammonium concentration in urine also varied from 2000 to 4 000 mg/L (as ammonium-nitrogen), one **column of 120 L** liquid volume was able to treat from 6 to 100 L urine per day. In the EWAG pilot-plant, urine typically has an ammonia concentration of 1 800 mg/L (as nitrogen), meaning that 50 L could be trated daily.



Urine collected in urine-diverting toilets or urinals contains bacteria that convert urine into a malodourous liquid with high concentrations of volatile ammonia (NH_3). The nitrification column has the task to stabilize urine and make it easier to hanlde. Here, bacteria oxidise half the ammonia into non-volatile nitrate (NO_3^-) and, as the pH drops, the other half is stabilised as non-volatile ammonium (NH_4^+). This way, final nitrate ammonium ratio is equal to 1.

Laboratory scale nitrification plant

Nitrification plant in the EWAG Customer Centre in South Africa

Distillation	Sheet nr. 8

To concentrate a solution, distillation is a well-known process. In the case of nitrified urine, water is the component with the lowest boiling point. Hence, at a certain temperature, water evaporates and leaves behind an increasingly concentrated solution. The nitrified urine is distilled in order to reduce its volume and minimize costs for storage and transportation. Furhtermore, the high-temperature process pasteurises the solution.

State-of-the-art distiller with vapour compression used in the VUNA project

Operating characteristics and outcomes of the distiller used in the VUNA project are reported below:

- Distillation efficiently concentrates urine nutrients into a liquid fertiliser.
- Nitrogen loss during distillation is very low (below 1.5 %, if the initial pH value is 6).
- Producing liquid ammonium nitrate is safe as the maximum operating temperature is far below the critical 165 °C.
- Solid ammonium nitrate must not be produced at temperatures above 96 °C, to avoid risk of explosion.
- Complete nitrification to nitrate (by adding calcium carbonate) increases thermal stability.

About 800 mL of concentrate or 600 g of dry solids can be produced from 20 L of nitrified urine.

Key figures

Maximum water removal from nitrified urine (ammonium nitrate)	97 %
Maximum sodium chloride removal from nitrified urine (ammonium nitrate)	50 %

Distilled liquid	Nitrogen loss
Stored urine (pH 9)	93 %
Nitrified urine (pH 6)	1.5 %

Final product	Maximum operating temperature
Solid ammonium nitrate	96 °C
Liquid ammonium nitrate	165 °C
Solid nitrate	> 360 °C

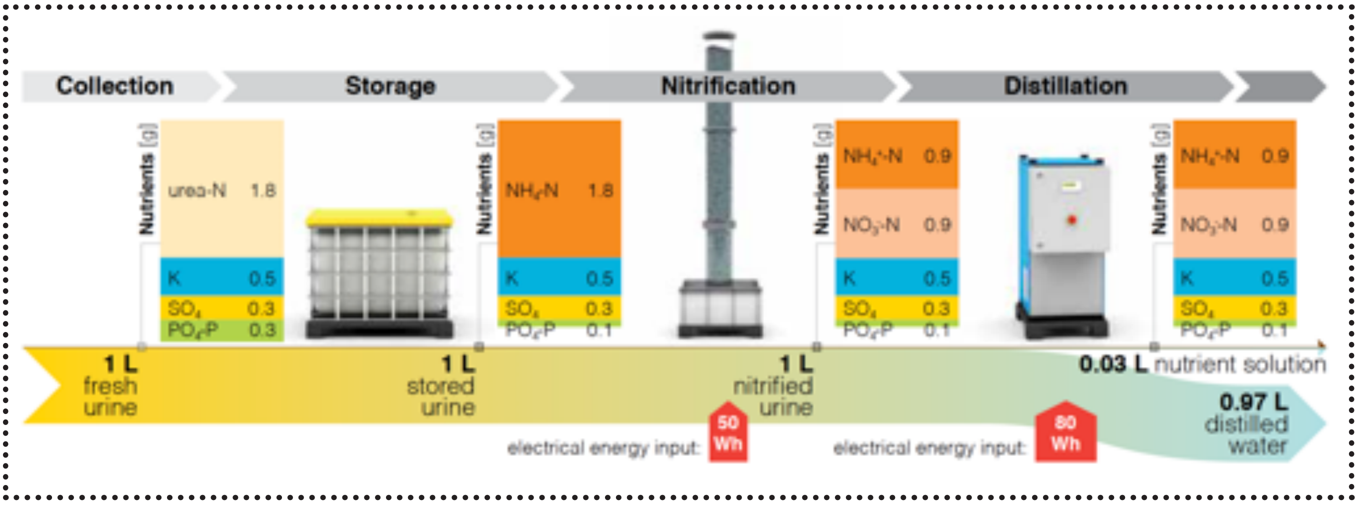
Concerning the distilled water as output of the distillation process, it must be taken into consideration that it may contain some impurities, particularly a residual ammonium concentration of 30 to 60 mg/L is typical. Furthermore, a thin oil layer can sometimes be observed floating on the distillate, originating from tiny leakages in the vacuum pump. Considering these impurities, there are different ways to reuse the distillate:

- Toilet flush water: distillate water can be diluted with rainwater or treated greywater for flushing purposes. Dilution ratios from 1:100 down to 1:20 are proved to be efficient and no odours or other compromising effect is observed in the flush water.
- Irrigation: The distillation water can be used for irrgating field-crops or hydroponic crops. In field cultivations the low content of ammonia concentration present in the distilled water proved not to be an issue for the crops.

The whole treatment for complete nutrient recovery	Sheet nr. 9

Differently from the other methods analyzed in this research, like struvite precipitation and ammonia stripping, the process for complete nutrient recovery takes a different approach. Instead of targeting nutrients to remove from the wastewater, complete nutrient revovery removes water so that most all the nutrients remain in a concentrated nutrient solution. To do so, urine must be stabilize via nitrification to avoid ammonia volatilization. The final products of the complete nutrient recovery process are then: i) distilled water that can be reused for irrigation, and ii) a concentrate nutrient solution.

Complete nutrient recovery process as shown in the VUNA final project report (2015)



Real life operating system. Images retrieved from *Vuna Handbook on Urine Treatment (2016)*

System components

0. Storage tank
1. Nitrificaiton columns
2. Intermediate storage tanks
3. Vacuum distiller
4. Distillate tank
5. Nutrient concentrate tank
6. Process control unit
7. Aeration control
8. Vent pipe

The complete installation has a footprint of approximately 5 m2

The room accommodating it should not be smaller than 10 m2 for a 120 L reactors

System footprint: 10 sm

Source: Interview conducted during the research period to Bastian Etter, managing director of the VUNA project

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PART 3: Assessing the methodology for the design of Building-integrated agriculture models incorporated with wastewater treatment systems coupled with hydroponics

- Chapter 5: Developing a methodological approach for the complete recovery of water and nutrients in Building-integrated agriculture projects

Chapter 5: Developing a methodological approach for the complete recovery of water and nutrients in Building-integrated agriculture projects

Preface

The new circular strategies promoted by the European Union [1] and adopted by the Member States mark a turning point in the way food and diets are perceived in urban areas. Indeed, food, water, and nutrients, as well as buildings and construction, are now key products in the development of new urban value chains [1]. New regulations to reduce food waste and implement the sustainability of food distribution and consumption are being developed by the European Commission that is determined to dramatically reduce the negative impacts of resource extraction and environmental pressure of which the current food value chain is responsible. In this regard, the Commission has developed two crucial strategies, which can implement the circular reuse of nutrients and reclaimed water in agriculture:

i) The new Water Reuse Regulation [2] aims to encourage circular approaches towards urban wastewater reuse in agriculture, providing the Member States with precise water quality standards for irrigation.

ii) The proposal for an Integrated Nutrient Management Plan [3], with the objective to ensure more sustainable application of nutrients.

In this framework, European municipalities are including (peri-) & urban farming projects in spatial planning, encouraging food production initiatives that can boost the transition towards new circular models for the production and consumption of food in urban areas. In this scenario, vacant urban spaces, as well as roofs, facades, and entire buildings, represent the ground zero for the integration of off-soil food systems within the built environment. Thus, food production systems could be considered a new full-fledged construction technology that may implement the overall sustainability of buildings, districts, and cities, promoting resource recycling, fostering a new urban circular economy of food. ZFarming and BIA projects will be then a smart solution to integrate sustainable architecture with circular production of food. In this sense, in the previous chapter, this thesis has explored the potentiality of water and nutrients recovery from domestic wastewater, reviewing the literature and analyzing the case studies that promoted the use of wastewater-based nutrient solutions for hydroponic production. However, to fully address the potential of these technologies, their applications on real-life pilot projects is essential. Thus, this final chapter will explore the efficiency of nutrients recovery and food production on a specific case study, to theoretically determine:

- How much water can be saved by reusing treated greywater for food production and other non-potable uses (washing and flushing).
- Production capacity and limitations of food crops cultivated in hydroponic with urine-based nutrient solutions.
- The total surface needed for food production to satisfy local food demand of cultivated fruits vegetables.

The site of intervention is located in Amsterdam, in the maritime west coast climate. The selected area is part of a new development plan aiming at hosting from 3 to 5 thousand households in the east part of the city. Approximately 10% of the developing area has been left for urban experimentation and will host around 500 households. The proposed project will be developed on that fraction of the development plan, and municipal requirements will work as inputs for the design of a BIA small district (Fig.1). The area of intervention is then a canvas where to develop and assess the efficacy of a broader methodology for the design of green, food-productive residential buildings. The aim is to determine the correlations between hydroponic food production and citizens' lives.

Fig 1: The development of BIA districts. Conceptualization

Source: *Own work*

Thus, the final objective of this last chapter is to develop a methodological approach for the design of BIA projects, and apply this methodology to a selected case study. The proposed methodology is specifically thought for the selected scenario of intervention (see Ch. 3: Climatic area CfB [4]), but can be also adapted to other climatic and cultural contexts, providing a set of broader guidelines that will guarantee the correct application of off-soil food production systems integrated into the architectonic landscape. The main topics that will be addressed by the methodological approach are connected to:

i) The selection of crops and production methods for healthy and smart hydroponic food production in urban areas.

ii) The necessity to close the loop of water and nutrients in urban areas, quantifying the actual benefits of doing so in new development areas.

iii) Construction and spatial requirements of the hydroponic food production system within buildings and relatively small districts.

1. The methodological approach

The development of the methodological approach was done in concert with the department of Greenhouse Horticulture at Wageningen UR with the objective of implementing a general methodology for the development of BIA projects that aim at recovering nutrients and irrigation water from domestic wastewater. The proposed methodology was then applied to a specific case study in Amsterdam following the principle of the "research by design" to theoretically assess the impact of wastewater recovery on buildings of a new construction district.

The choice to operate in a given context was crucial to obtain social and economic parameters that were given by the development plan. Such parameters will work as fixed inputs for the design of BIA concepts where the hydroponic production is confronted with wastewater recycling. In this scenario, developing a broad methodology was then fundamental to adapt the design principles to possibly different inputs provided by other plans or other contexts. This way, the methodology here proposed is intended as a compendium of operational guidelines for the development of similar BIA projects. The other inputs necessary for the design proposed in this final part of the thesis were extrapolated from the whole research experience as reported below:

- Food and plants integration strategies: Chapter 2
- Circular economy for sustainable urban food production: Chapter 2 & 3
- Hydroponic technologies and enclosures: Chapter 3
- Strategies for the integration of off-soil food production systems in buildings: Chapter 3
- Climatic and social context: Chapter 3
- Nutrients recovery technology from urine: Chapter 4
- Water recovery technology from greywater: Chapter 4
- Quantity and quality of reclaimed water: Chapter 4
- European water reuse guidelines and discharge standards: Chapter 4

Based on the knowledge developed during the whole period of the research and the inputs extrapolated from the previous chapters, it was possible to propose a methodological approach for the design of BIA buildings and districts. The proposal will then be confronted with a real-life case-study to assess its strength and limitations. As a conclusion, a final methodology will be developed based on the results of the application of the methodological approach to the case-study. The proposed approach was developed as follow:

Step 1: Crops choice
The first step consists of determining the crops that can be grown in a certain area, based on nutritional proprieties of the crops, local diets, food availability, and indications provided by the European Food-Based Dietary Guidelines (FBDGs) [5]. The objective is to select those crops that could potentially implement citizen's health, by choosing those that can guarantee maximum nutrients intake and, at the same time, provide optimal growing performances in hydroponic systems. This step is crucial to assess the efficacy of BIA projects in producing enough food for the local communities that could potentially satisfy the local food demand of certain given fruits and vegetables. Furthermore, crop choice highly influences nutrients and water inputs of the hydroponic systems, thus, water and nutrient quantitative analysis could not be made without knowing which plants will be produced. In conclusion, crop choice has been determined to be the first step as it can influence all other design choices. From this step, the following outcomes are expected:

- Selected crops that can be produced in a hydroponic system and that can guarantee high nutrient intakes.
- Enclosures and hydroponic methods that best fit each selected crop production.
- The production capacity of each selected crop.
- Water and nutrients requirements of each selected crop.
- Desired consumption of fruits and vegetables in the chosen area of intervention.

Step 2: Determine spatial requirements

Once assessed the crops that will be cultivated in the integrated hydroponic systems, as well as their production capacity and enclosures, it would be possible to determine the dimensions of the production spaces. Hence, the second step consists of assessing spatial requirements for the production of urban crops. The objective of this step is to understand how production spaces can interact with the building construction, influencing design choices that will characterize the final project. To do so, a simple equation has been written that puts into relation the expected number of inhabitants of a building (or a district) with the total production capacity of each crop, and the total estimated consumption of that specific crop. Inputs such as production capacity and estimated consumption were derived from step 1. from the analysis of FBDGs, and the reported characteristics of the selected crops. Expected outcomes of this step are:

- The total production capacity of the BIA system.
- Estimation of the hydroponic system dimensions.
- Indications for the design integration of the hydroponic systems within the building/district.

Step 3: Assess domestic wastewater characteristics

Based on the considerations reported in Chapter 4, a qualitative and quantitative analysis of domestic wastewater characteristics is crucial to balance water masses for hydroponic production. Domestic wastewater characteristics are strictly connected to the area of intervention, as they highly depend on people's habits and diets. Generally, for European countries and major cities, these characteristics can be found in the literature. However, urine and greywater analysis may be crucial in case they are not referenced in the literature. Knowing the characteristics of the wastewater that will be treated, will also help with choosing the treatment systems, as well as dimensioning the required storage and water tanks. Hence, the third step consists of reviewing the information regarding domestic wastewater characteristics of the specific area of intervention, and, based on that, balance the water masses that will flow in the building/district. Inputs concerning the dimension of the installation rooms will also be provided. Expected outcomes of this step are:

- Quantity of yellow water flowing from the building and relative nutrients concentration.
- Quantity and quality of the greywater coming from toilet flushing and washing activities.
- Typology of the treatment technology and dimensions of the installation rooms.
- Quantity and quality of the treated wastewater.
- Dimensions of the storage tanks and the disinfection tanks.

Step 4: Verify the feasibility of the system

The fourth step consists of comparing all the outputs of the previous three steps and provide final inputs for the design of the BIA project. For instance, based on the analysis of the water quality in Step 3, it would be possible to adjust the production capacity of the selected crops based on the availability of the specific nutrients. Different production capacities may influence the dimensions of the hydroponic system assessed in Step 2, thus, further remodeling of the enclosures and the interior production spaces may be required to provide optimal wastewater treatment. Finally, the objective of this final step is to assess the efficacy of the specific BIA project concerning wastewater treatment and related food production. Comparing the outcomes of the other step would guarantee the development of the needed calculations to assess the actual gain in terms of water and nutrients that the project could provide. Thus, the expected outcomes of this step are:

- The effective production capacity of the whole BIA system.
- Final dimensions of the production spaces.
- Determine the actual efficiency of the BIA system in terms of water and nutrients gains.

Fig. 2: Methodology for the development of BIA projects with regards to wastewater recovery

STEP 1: CROPS SELECTION

Starting from EU indications, it is important to choose crops families based on their nutritional values and their health benefits. This choice starts from general considerations that can be valid for every city and country in Europe, and proceed to more site-specific considerations which are fundamentals to choose the right crops

General Considerations:

1. Analysis of most common Vitamins and Minerals and their reccomended intake
2. Associate and choose crops based on their nutritional values
3. Determine which crops can be grown hydroponically

Site-specific Considerations:

1. Based on local diets define production percentage of vegetables and fruits
2. Assess the productivity of the chosen crops, and relative production methods
3. Asses the growing requirements of the chosen crops

STEP 2: SPATIAL REQUIREMENTS

Based on the chosen crops, determine the spatial requirements of the hydroponic food production systems

1. Based on the production capacity determined in the first step, assess the most convenient method to produce each selected crop.
2. Based on local dieteray guideliines define the range of desirible consumption of vegetables and fruits in terms of gram per day per person
3. Put consumption and production in relation with the expected number of inhabitants living in the building/district

$$D = \frac{Sp \cdot \bar{p}\,\frac{g}{day}}{\sum_{i=1}^{n} I\,(sm) \cdot C\,\frac{g}{day}}$$

C represents the desirable consumption indicated in the local FBDGs

$\bar{p}$ is the global average productivity. It will change per each crop based on the used production system

per **D=1** the local demand of vegetables and fruits is satisfied

Sp indicates the production surface

$\sum_{p=1}^{n} P(sm)$ indicates the number of people living in the building/ district as sum of people per sm

STEP 3: ASSESS DOMESTIC WASTEWATER CHARACTERISTICS

Based on the location of the project, it is possible to know wastewater chararacteristics. Quantity and quality of urine and greywater must be assessed in order to determine their possible reuse

Detrimne urine quantity and composition to assess the quantity of nutrients that can be retrieved from the source

Detrimne greywater quantity and composition to assess the quantity of irrigation water that can be reused

Assess the dimenstions and funtioning of on-site recovery technologies for wastewater treatment

STEP 4: VERIFY THE FEASIBILIITY OF THE SYSTEM

The last step consists in comparing the resource outputs coming from the building (in terms of nutrients and water) with the needed plants input requirements. Theoretical calculations can be made to assess the percentage of production that can be self-sustained by the use of recycled nutrients and water

Calculate the estimated productivity that can be reached by the system using recycled nutrients from urine-based fertilizer

Calculate the total amount of water that is needed for irrigation in each crop and determine the overall gain in terms of fresh water consumption

Evaluate the dimensions of the production spaces for proper wastewater treatment, and assess the feasibility in terms of space requirements.

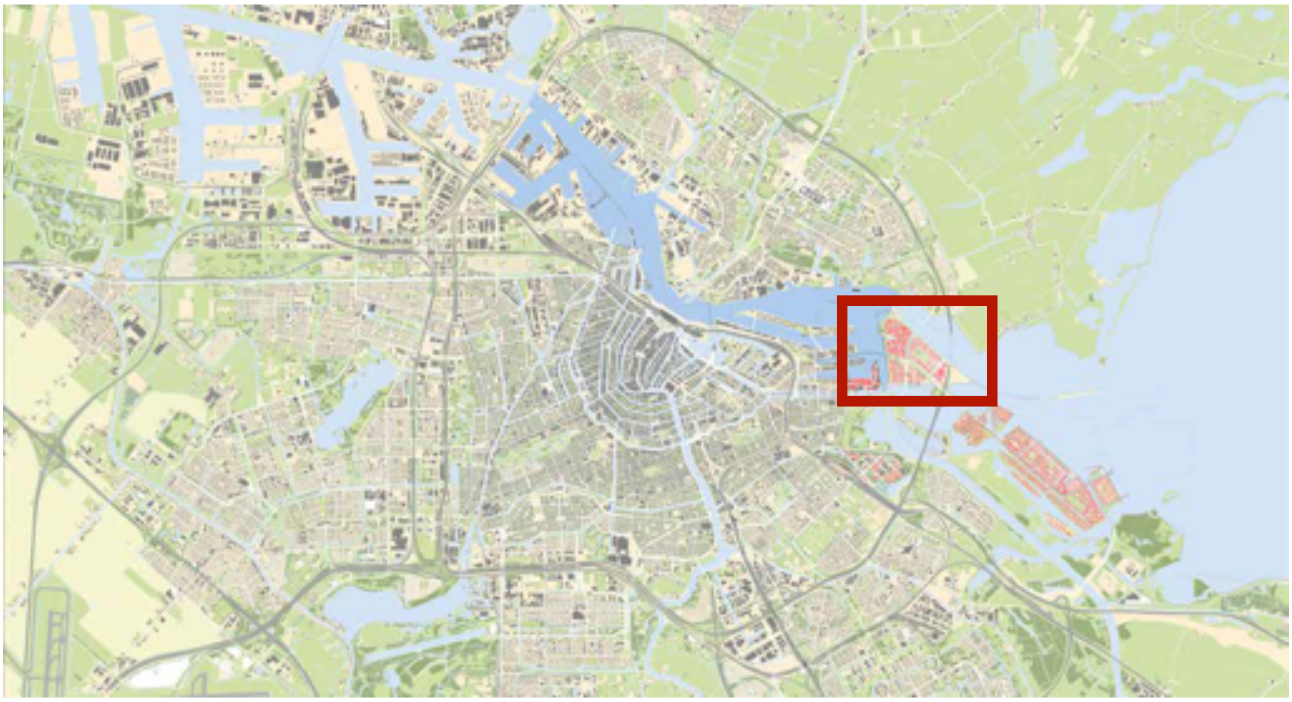
OUTCOME: DESIGN OF THE INTEGRATED SYSEM

Source: *Own work*

2. The selected case study: the new development plan for the Sluisbuurt neighborhood in Amsterdam

The population of Amsterdam has grown rapidly in recent years with an average annual increase of 10.000 inhabitants since 1984 [6]. In this scenario, the municipality of Amsterdam has developed specific policies to facilitate this growth and at the same time reduce pressure on the housing market. The goal is is to enable the construction of 52.500 homes within the city boundaries by 2025 (around 5.000 homes a year). To this concern, several areas were identified to address this goal, which are summarized in a medium-term municipal development strategy "Setting the course for 2025 - Space for the City" [7]. This strategy focuses on increasing the densification of the urban environment with an attractive and diverse urban planning. Within the areas listed in the development strategy, this research will operate and propose a pilot project on the Sluisbuurt area, as testing case study for the application of the proposed methodology. The Sluisbuurt is located on a waterfront in the northwestern part of the city within the A10 highway ring, overlooking the IJ river and the inner city and it is connected via the Piet Hein tunnel to the center of Amsterdam (Fig. 3). The proximity to the city center offers opportunities for a highly dense urban environment creating a living/working environment with many facilities and low car use. The spatial assignment is to offer specific qualities in one forward-looking plan, in line with the changing wishes of the Amsterdam population and new types of employees. The new plan for the Sluisbuurt area is aiming to build around 5.500 homes for about 11.000 inhabitants [8], in addition to a maximum of 100,000 m² of non-living green areas, consistently with the objectives described in the Amsterdam Stuctural Vision 2040 [9].

Fig. 3: The location of the Sluisbuurt area within the city of Amsterdam



Source: *Gemeente Amsterdam (2017), Stedenbouwkundig Plan Sluisbuurt vastgesteld door de Gemeenteraad op 27 september 2017 [8]*

Strategies for the development plan of the Sluisbuurt area

The plan is developed to host a minimum of 3.500 and a maximum of 5.500 houses in a high dense construction environment (density: 200 households per hectare). In this regard, several key development points have been developed by the municipality to address the challenge of creating a high quality urban living environment within a high density district. The key strategies are reported below, and worked as inputs for the development of the plant which will be further discussed later on.

Key points:

- The construction of approximately 3.500 to 5,500 homes with preservation of living quality and protection of surrounding landscape through densification in the urban area;
- Make maximum use of the quality of the location, located within the ring and on the water, intertwined with the surrounding landscape;
- Strengthening the urban structure, in particular in the IJburg (a new construction neighborhood located in the western part of Amsterdam [9]) - city center connection as a link to function with the city;
- Orientation on the city center and be part of the waterfront on the IJ river;
- Strengthen the spatial identity of the city with a powerful, new silhouette;
- Design the Sluisbuurt based on the policy principles of The Moving City, where cycling, walking, sports and exercise are central and the car gets a subordinate role;
- Develop the Sluisbuurt in a sustainable way, both environmental and social.

With reference to the reported key points, the plan aims to make space for a new generation of starters, young families and elderly who also want to live in the city, nearby work and facilities. The living program consists in 500,000 m² gross floor areas (GFA) of housing, The need for a new type residential environment in the city is the reason for this urban development plan with a maximum target of 5,500 homes, which are divided in various typologies. The living program of the Sluisbuurt includes about 40% social rental housing (including one part student / youth housing) and 60% free sector available for renting or buying. Attention is also paid to the development of medium-sized homes for people who earn too much for a social rental home and too little for an average free sector home. In addition to homes, a maximum of 100,000 m² gross floor area (GFA) will be added non-living development. This does not only include neighborhood facilities, workspaces and commercial functions, but also large facilities on urban level, such as a high school and a college. The plan refers to the Sluisbuurt as a "Creative neighborhood", where residential and work areas are mixed with independent office spaces. The ratio between the number of jobs and number of inhabitants in this neighborhood is to be considered 1: 4.

Due to the high density of the Sluisbuurt neighborhood, specific guidelines concerning the sustainability and livability of the constructed space were provided by the plan as follow:

1. *Water resiliency*: The Sluisbuurt is set up to be "rainproof". Water collection of extreme waterfalls is solved by one robust system of water basins. Excessive water is though to be relieved in the Amsterdam Rhine Canal though a new installed system of water circuits. Green roofs and gardens are of added value as regards reduction / prevention of adverse effects of heavy rainfall.

2. *Green facades and roofs:* They could also contribute to a water-retardant effect and a better water management. Furthermore, the focus of The Green Agenda 2015- 2018 includes the addition of 50,000 m² green roof in Amsterdam, to both improve resiliency to rainwater and provide additional cooling in summer. Roofs will be used for the development of collective roof gardens and for the installation of solar panels (yellow roofs). In this regard, a minimum surface of 30% of the total rooftop spaces is destined to solar energy production.

3. *Foster a local circular economy:* During the development of this research, it was possible to analyze and report some key features of the circular developing plan made by the municipality of Amsterdam [10]. In this regard, the plan for the Sluisbuurt area intend to implement circular strategies especially concerning waste separation and raw materials collection. Regarding circularity of the buildings, flexibility is the keyword. Building shapes and construction systems

should be easily adjusted in such a way that function mix and adaptation of different housing typologies would be easy to achieve.

4. *Waste:* As previously written, specific strategies have been developed in the Netherlands and in Amsterdam to treat waste. National targets set the goal to separate 65% of household waste from 2020 [11]. Waste includes paper, glass, plastic, vegetables / fruit, textiles and residual waste from wastewater. To facilitate the collection of waste, the plan intends to separate them at the source and collect them in fractions. Due to the high density of the neighborhood, more waste is expected to be generated with the result that waste collection has an explicit impact on the public space. In this regard, a local collection and treatment coupled with a smart underground transportation system has been developed in the plan to reduce the amount of waste containers and transport movements in the neighborhood and in the city.

Building and clusters development guidelines of the plan

The urban development plan for the Sluisbuurt consists of ten building clusters (Fig. 4A) of approximately 1 to 2.4 hectares of gross area. Allowed building surface is coherent with the indications provided by the vision for Amsterdam 2040 [9], and corresponds to a floor surface index (fsi) of 2.8 to 4.8 m² GFA per square meter of land. Each cluster contains public spaces to be further developed on a second phase. The public space in the clusters can consist of parks, crossings, slow traffic routes and a public waterfront walk. The urban fabric is composed by a mix of building blocks and towers of different heights with different shapes and envelopes in order to implement urban diversity and variety of construction. Indeed, diversity has been considered a prerequisite of the plan, and the definition of the construction program is a direct consequence of it. The building program consists in the following elements (Fig. 5):

- Basic building blocks: the building blocks are thought to be around 20 meters high, and can reach 30 meters following the axe N-O. Higher and lower buildings together form a block, with different housing typologies.

- Towers: The towers, the "vertical city", are the integral part of the tissue, and must not be considered solitary elements in the green. Attention must be paid to the transition between high-rise buildings and public spaces. In the plan there are twelve towers with building heights between 40 and maximum 80 meters and five towers with construction heights between 80 and a maximum of 125 meters (Fig. 4B). The highest towers are placed to the north so that their shadow won't affect the public ground area. The northern part of the Sluisbuurt is also the most visible part from the IJ river (Fig. 4C). The towers are placed alternately, with sufficient distance from each other in order to improve visibility and sunlight; a transparent silhouette is a consequence of this

- Plinths: The ground floor of each building will accommodate social and working functions. Plinths must be at least 3.5 meters high, even higher up on the main road. For workspaces a double height is desirable. As a result the ground floor is flexible in use, also for commercial and social facilities. This promotes the social safety and liveliness in the street. Bicycle sheds and storerooms are integrated. in the lower layers of the buildings.

- Amenities: amenities are often in the plinths but can also be found on higher floors. In this way there is also 'made in the high city', including the Associated facilities (e.g. rooftop bar, playground etc.). The rest of the green spaces can take various forms and is integrated into the block: green roofs, facades, (common) gardens and pocket parks. This space is intended to offer intimacy, tranquillity, protection and greenery, as well as to provide ecological added value and contribute to reach the water management goals.

Fig. 4: Urban fabric of the Sluisbuurt neighborhood

Legend: Fig. 4A represents the division in 10 cluster of the whole area; Fig. 4B shows the heigh and disposition of the towers; Fig. 4C shows the distribution of towers' height towards the north part of the neighborhood.
Source: *Gemeente Amsterdam (2017), Stedenbouwkundig Plan Sluisbuurt vastgesteld door de Gemeenteraad op 27 september 2017 [8]*.

Fig. 5: Characteristics of the building's typologies

LOWER BUILDING BLOCKS - Up to 15 m
550 households
10% of the total

APARTMENT BUILDING - Up to 20 m
3575 households
60% of the total

TOWERS - Up to 80 m
825 households
20% of the total

HIGH TOWERS - Up to 125 m
550 households
10% of the total

Source: *Gemeente Amsterdam (2017), Stedenbouwkundig Plan Sluisbuurt vastgesteld door de Gemeenteraad op 27 september 2017 [8]*.

Nature-based buildings: water and green as resources

In view of the high building density, a green design is of great importance to increase the livability of the area. Furthermore, a green design that involves integrating the green within buildings, as well as a proper water management, would improve the environmental feasibility of the plan, and, at the same time, increase the quality of the living spaces. Opportunities can be sought in particular in roof gardens, green walls, green public spaces and public/private gardens. The plan set the goal of having at least 30% of the roof surface planted in building blocks up to 20 meter. This is reported to have a major impact on the overall livability of the neighborhood, providing the desired image quality from the street level.

Green public spaces can be used for an additional contribute to the quality of life in the neighborhood. In these places trees can improve the living environment. In the building plan, explicit attention should be paid to for the construction, management and maintenance of the green on public and issuable property. This with with a view to maintaining a high quality appearance of the building and area. Finally vertical greenery is highly recommended. Green walls and facades should be planted with high aesthetic value plants plants that would enhance buildings' appearance from the street level. Additionally to the greening policies of the plan, water storage and high retention green roods must be included in the design of the buildings. Water tanks are required and needed to delay water remittance. In this regard, drained water effluent should reach the sewage system at a maximum rate of 0,9 mm/hour (2,5l/s/ha).

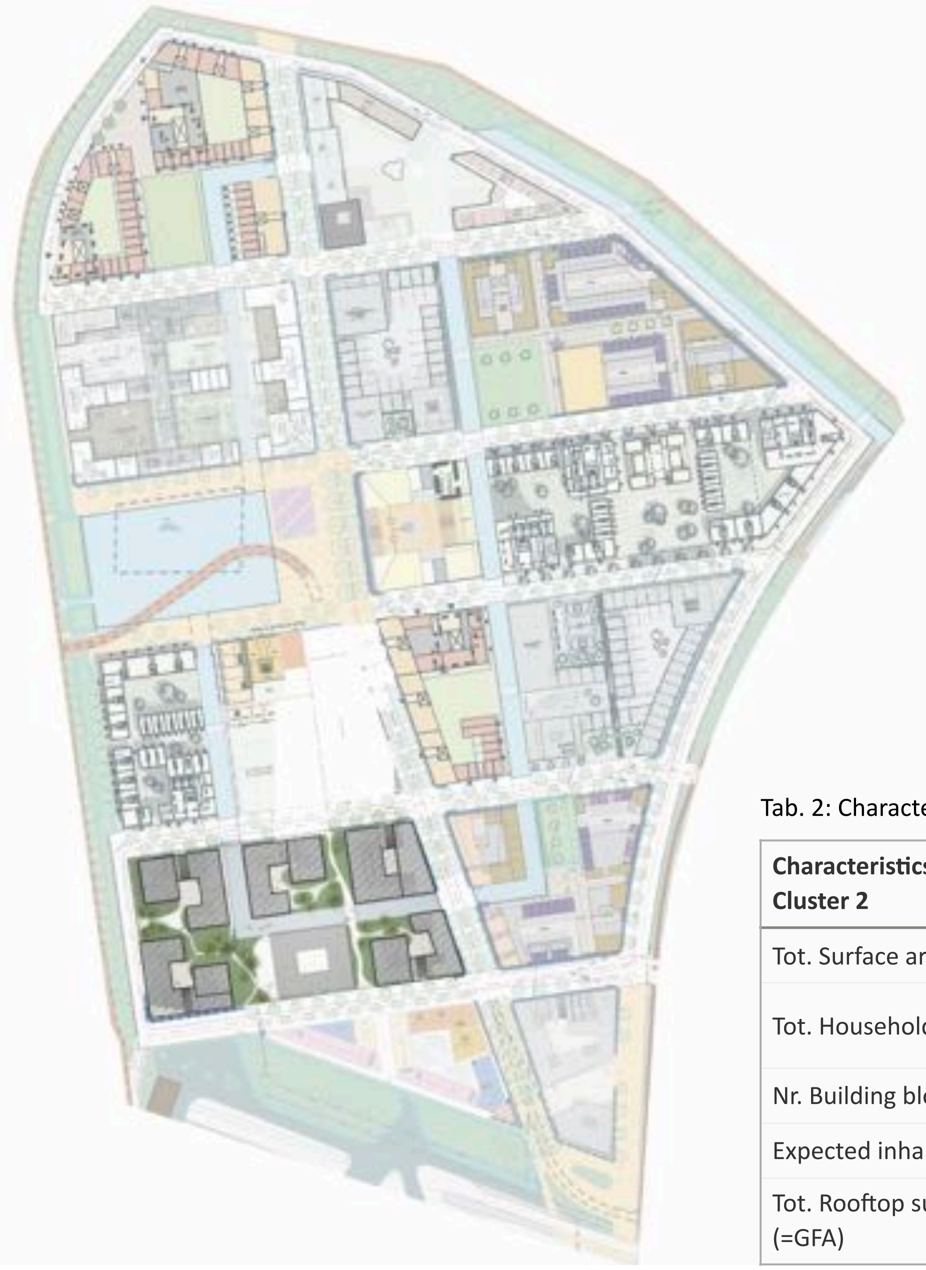
2.1 Application of the methodological approach to a selected area of intervention

Considering the premises and the objectives of the plan, briefly reported in the few pages above, the Sluisbuurt area presents the necessary characteristics to propose a BIA project that is able to recover and treat wastewater. Furthermore, a specific characteristic of the development plan made it suitable for this experimentation, hoping that further discussion with the municipality would be taken into consideration. It is explicitly written in the plan that a total of 10% of the issuable terrain (within the maximum program) is considered to be further developed and entirely dedicated to urban experimentation and innovation both in built form and as an open space. The experimental activities should be determined on the basis of the needs of the residents, market demand and initiatives in the city. The infill, which is still not be determined in the Urban Development Plan, is diverse and can vary from playground and educational vegetable gardens to temporary parking garage, special housing program or commercial facilities. To this concern, one tenth of the plan (approximately corresponding to one cluster) has been chosen to further develop the founding of this research with the objective to confront the design a BIA model for urban food production and wastewater treatment with a real life scenario. Of the ten clusters reported in Table 1, the design of the BIA model will be developed in cluster 2 (Fig. 6). The reasons standing behind the decision of setting the experimentation project in Cluster 2 mostly derived from the fact that it will be developed in a later stage of the construction plan. Furthermore, the total surface area (approximately 2 hectares) and the total number of households (max 390) divided in five blocks are coherent with the hypothesis extrapolated from Chapter 4 for the implementation of an effective BIA district integrated with on-site wastewater recovery plants.

Tab 1: Programmatic specification of the Sluisbuurt neighborhood

Clusters	Net residential functoins max m² GFA	Housing program max number of housing	Reserved for education min m² GFA
Cluster 1	5000	700	primary school - 2000
Cluster 2	**13000**	**390**	**secondary school - 8000**
Cluster 3	4000	310	-
Cluster 4	5000	390	-
Cluster 5	12000	570	primary school - 3500
Cluster 6	40000	500	high school - 25000 primary school - 2000 primary school - 3500
Cluster 7	9000	1000	primary school - 3500
Cluster 8	3000	380	-
Cluster 9	3000	680	-
Cluster 10	5000	580	primary school - 2000

Fig. 6: Localization of Cluster 2 within the neighborhood



Tab. 2: Characteristics of Cluster 2

Characteristics of Cluster 2	**Dimensions**
Tot. Surface area	1.9 ha
Tot. Households	390
Nr. Building blocks	5
Expected inhabitants	780-860
Tot. Rooftop surface (=GFA)	13.000 m2

3. Application of the methodology to the chosen location

Once the location has been chosen, the inputs coming from the municipal developing plan can be added to the inputs extrapolated during the research process concerning food production methods and hydroponic wastewater treatment technologies. The methodology is here applied to Cluster 2 of the Sluisbuurt development plan. The main objective is to evaluate the possible impact in terms of production, as well as nutrients and water recovery, of a building-integrated agriculture small district in a real-life situation. Expected outcomes from this process are:

- Estimation of the number of fruits and vegetables produced by the urban hydroponic system and compare this data with the actual food demand of the selected location.
- Estimation of the dimensions needed for the hydroponic food production systems to meet the local food demand.
- Define the best wastewater treatment technology for the specific project and theoretically calculate the quality of the discharge water.

- Define the dimensions of the decentralized integrated wastewater treatment plants.
- Calculation of the amount of nutrients coming from domestic wastewater that can be transformed into the nutrient solution for the plants grown in the hydroponic systems.
- Calculation of the percentage quantity of reclaimed water that can be used for irrigation and other non-potable uses.

The methodological approach for the design of the BIA cluster will follow the steps described in the first paragraph with the aim of assessing its strengths and limitations.

Objective of the project

As repeatedly stated in this research, urban farming is unlikely to provide urban areas with all of its food needs. Intensive vertical farming systems might have a deeper impact on food production compared to UA soil-based initiatives. However, the integration of advanced food production systems within residential buildings would not have the sufficient surface to have a great impact on the municipal food system, unless it is spread all over the city with the possibility to differentiate production and involve a greater number of people. For this reason, the objective of this project is to experiment with building-integrated agriculture and asses its production capacity with respect to the circular strategies of wastewater treatment and recovery. Hence, the produced food is not intended for commercial purposes, but as a tool for raising awareness on important topics such as food safety and healthy diets. In this sense, the choice of crops will be done following this objective, by selecting those crops that can maximize nutrients uptake and that, based on their vitamins and minerals content, are considered to be more relevant to people's health. Thus, the idea is to propose a local food consortium, where all the produce from the hydroponic systems will hypothetically feed the local community only. Based on the production capacity and the potential demand, it will be possible to divide the estimated production costs by the number of people that could potentially have access to the food, so that the community could self-finance its food. This way, each member of the community will only pay an equal amount to self-sustain the production costs, and will be encouraged to eat the locally produced food as it will be then distributed to them without any further costs. Thus, determining the expected production costs and the total net production is fundamental to verify if a community food strategy is applicable. In this sense, consistently with the literature review and the analysis of the state of the art projects conducted throughout this research, it is strongly believed that the macro objectives of this and other similar BIA projects should be:

- Create new connections between people and food production by fostering local food consortiums.

- Raise awareness on the importance of healthy food and healthy diets.

- Communicate the feasibility of urine-based nutrients for the production of healthy crops, overcoming the possible skepticism concerning the use of wastewater for production.

3.1 Defining the production methods

As written in Chapter 3, there are two main types of enclosures for off-soil food production: greenhouses and indoor facilities. They both support hydroponic growing systems, but they are substantially different as the former uses solar energy to commence plants' photosynthetic processes, while the latter uses LED lights to substitute solar radiation as it is completely excluded from the exterior climate.

Considering the objectives of the project, it is important to choose the features that best fit the capacity of the system to maximize production and, at the same time, to absorb nutrients from the wastewater streams. The design of the enclosures follows the consideration done in Chapter 3, with a typical Venlo-type rooftop greenhouse with steel frame support, and an air-tight structure for indoor production. The characteristics of both systems, extrapolated from the literature review and deriving from the considerations expressed in Chapter 4, are reported below in Table 3:

Tab. 3: Characteristics of the production enclosures

Characteristic	**Integrated Rooftop greenhouses**	**Indoor facility**
Design	Venlo Type	Warehouse type vertical farm
Support structure	Steel frame / Aluminum frame	Building's construction structure
Covering materials	Glass - Standard single glass cover	Multi-layered walls
Growing method	Closed / Semi-closed system Hydroponic culture High wire DFT NFT Media-filled systems	Contained, stacked, hydroponic growing systems Growing beds Aeroponics
Energy inputs	Solar radiation, evaporative cooling, heating, fertilization, energy curtains	Forced ventilation, heating, sensible cooling, dehumidification, fertilization, Lighting system, CO_2 enrichment
Heating	Boiler + LED lights	Cogeneration - HVAC (forced circulation) Air cooler chiller
Cooling	Natural ventilation Fogging system Fan or Pad systems	
Lighting	LED	LED
Ventilation	Natural	Forced
CO_2	450 ppm - from air recirculation	800 ppm - from CO_2 enrichment

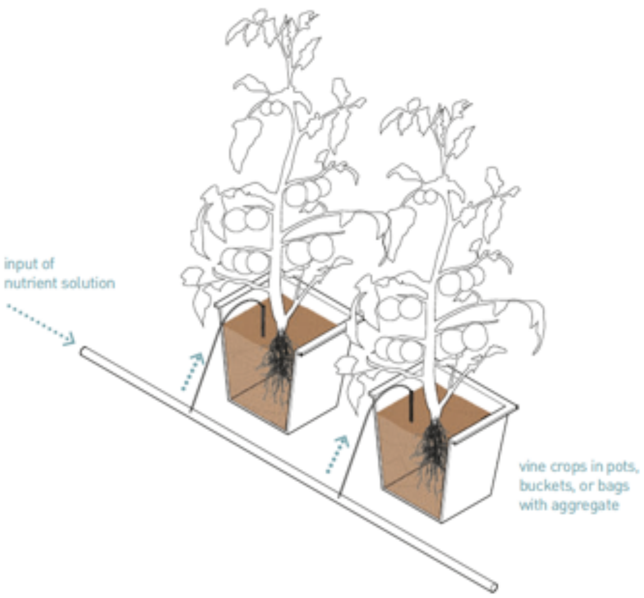
Table 3 indicates a broad spectrum of technologies and growing methods that can be used for the design of integrated rooftop greenhouses (iRTGs) and indoor facilities in dense urban environment in Cfb climates. For the purpose of this research, the characteristics of the two production methods listed in Table 3 will constitute the main reference for their set-up in the Sluisbuurt area.

Concerning iRTGs, they require specific energy inputs to control their indoor climates and improve environmental performances to facilitate effective and economical plant cultivation [13]. However, greenhouse operations largely take advantage of passive systems such as natural light and ventilation. Indeed, providing the right irrigation, ventilation, and a tolerable temperature range in a greenhouse is necessary. Nonetheless, supplementing naturally available energy and resources, such as sunlight, heat, and CO_2 may be optional but will surely boost yields, especially during darker, cooler winter months, allowing for year-round production [14]. Based on these considerations, it is important to assess which supplement can be sustainably given to the greenhouses in dense urban areas that won't affect the efficiency of the system and the health of citizens.

1. Growing methods must be chosen with regards to hydroponic wastewater treatment. As written in Chapter 3, closed or semi-closed systems are the best way to ensure constant irrigation and water recirculation, providing proper nutrient absorption, and wastewater pollutants removal. In this sense, an experiment conducted by Haddad and Mizyed [12] found

out that media-filled systems (with rock-wool, perlite, coconut-fiber, and clay beads substrates) provided the best yields and were the simplest method for wastewater treatment as they don't need separate biofiltration which instead is needed in NFT system to avoid clogging in the channels. Thus, the recommended growing method for iRTGs with regards to wastewater treatment is media filled system (Fig. 7).

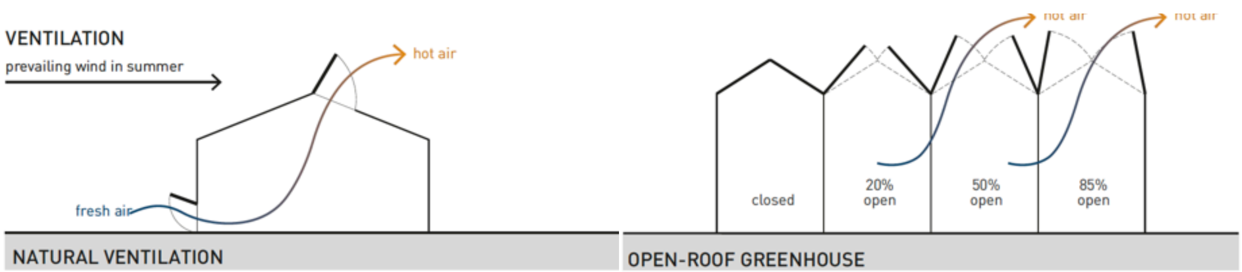
Fig. 7: Media filled system conceptualization



Source: *Proksch, Gundula. (2017). Creating Urban Agricultural Systems: An Integrated Approach to Design. Routledge, New York. [14]*

2. In greenhouses ventilation can be provided naturally. Ventilation systems help regulate air temperature by preventing overheating and replacing moist air with drier outside air to reduce the risk of disease while also supplying CO_2 [14]. Movable open roof greenhouses can offer a great number of variables as roofs can be opened up to 85% open to the sky (Fig. 8). This technology offers plants exposure to the outside climate and reduces energy needs for mechanical ventilation and cooling [14]. However, to provide the right amount of ventilation in high-tech greenhouses a certain level of automatization is needed in order to preserve production and safety.

Fig. 8: Greenhouse natural ventilation concepts

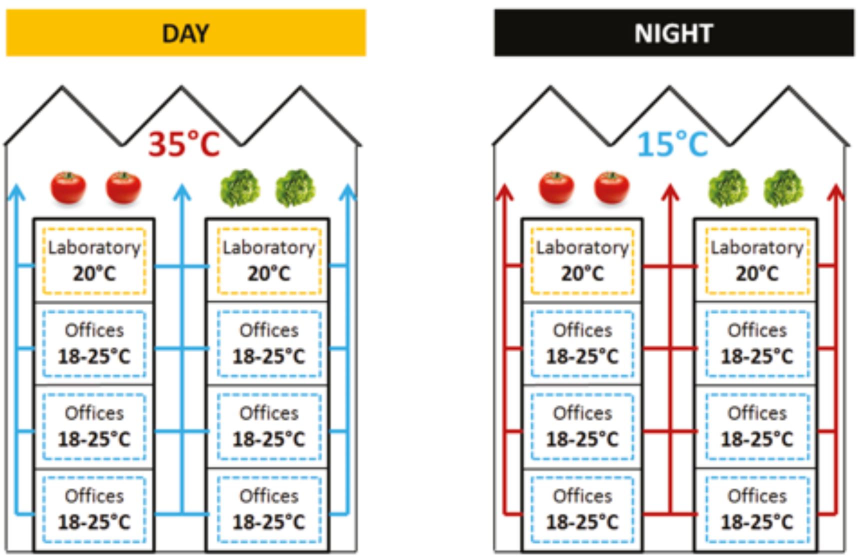


Source: *Proksch, Gundula. (2017). Creating Urban Agricultural Systems: An Integrated Approach to Design. Routledge, New York. [14]*

3. In greenhouses, heating is mostly needed at night, especially in winter [14]. Central heating systems can be designed by utilizing a central boiler to heat the water. Hot water produced by a boiler is pumped through pipes and delivered to the greenhouse. The temperature of the water circulating in the hot water system can be controlled to match the heat requirement of the system whether it is for floor heating, bench heating, top heating, perimeter heating, or snow and ice removal [15]. One advantage of this system is that the boiler can be positioned within the building and outside the greenhouse. However, new researches [16, 17] has demonstrated how iRTGs can benefit from the thermal differences between the building and the greenhouse (Fig. 9). In this case, residual air from the building can flow into the greenhouse, both for cooling and heating purposes. This way, the production system works as a thermo-regulator for the building, increasing the indoor thermal comfort, while regulating its internal temperature [17]. For this research, the possibility to exchange thermal flows between buildings and the greenhouse was acknowledged but not developed any further. The possibility to exchange heating and cooling between the two systems, however, can reduce the energy inputs needed for thermal control, thus, reducing the energy requirements estimated further on in this Chapter.

4. Concerning cooling, it can also be provided by natural ventilation especially in colder northern climates. However, evaporative cooling through fan or pad systems is the most effective alternative if natural ventilation fails to cool down the greenhouse [14]. These systems lower the temperature, increase humidity, and therefore reduce the water needs of plants. Thus, fan and pad cooling systems are based on the principle that evaporating water takes heat from the air. The same principle is applied to the fogging system, which utilizes high-pressure nozzles to form fine water droplets for cooling the greenhouse [15]. The smallest particles vaporize almost instantaneously, and the larger droplets are carried by air currents gradually becoming smaller until they are vaporized [15]. Nonetheless, similarly to heating, the greenhouse cooling can benefit from the integration within buildings. In this case, when temperature inside the greenhouse are too high, fresher air from the building can be introduced into the greenhouse, reducing the inner temperature (Fig. 9) [17]. However, the possibility to exchange thermal flows between buildings and the greenhouse was not developed any further in this research, and energy calculation were done based on the scenario in which the greenhouse uses only passive and active resources for heating and cooling.

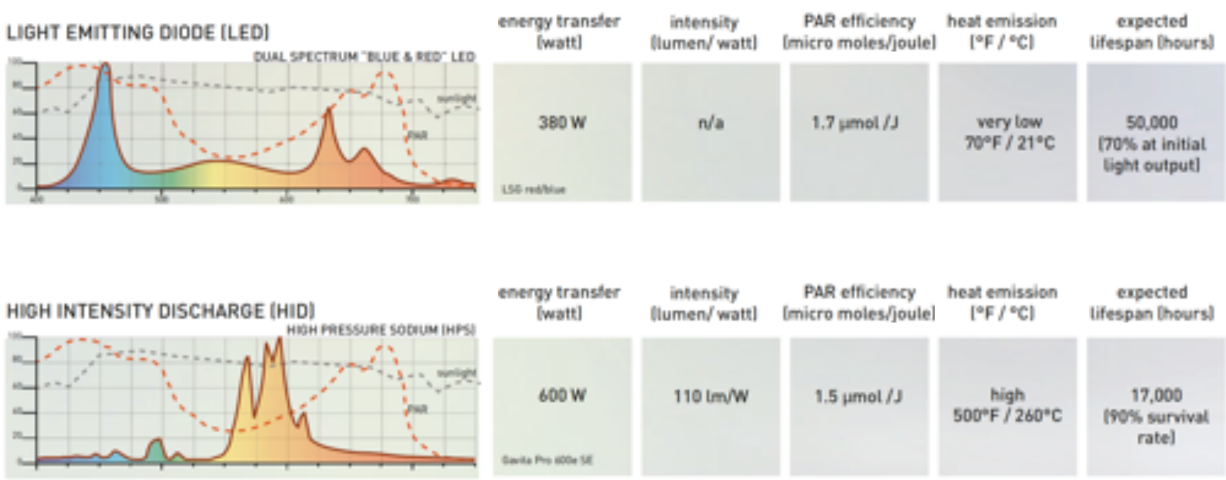
Fig. 9: Example of thermal energy exchange between the greenhouse and the building at the ICTA pilot building in Barcelona (ES)



Source: *Sanyé-Mengual, Esther & Llorach-Massana, Pere & Sanjuan-Delmás, David & Oliver-Solà, Jordi & Josa, Alejandro & Montero, Juan & Rieradevall, Joan. (2014). The ICTA-ICP Rooftop Greenhouse Lab (RTG-Lab): closing metabolic flows (energy, water, CO 2) through integrated Rooftop Greenhouses. 10.13140/RG.2.1.5016.7206*. [17]

5. Supplementing lighting can be crucial to achieving higher production, guaranteeing year-round greenhouse operations, especially in northern latitudes. In greenhouses the choice of whether to supplement light or not highly depends on the geographic location and the naturally available daylight [14]. As iRTGs have generally a narrower surface compared to conventional off-soil greenhouses, reflective surfaces should be incorporated in the surrounding walls (like installations partitions) and in the floor coating. In this sense, white paint and aluminum screens are viable passive solutions to increase light diffusion in iRTGs. Furthermore, in northern latitudes like the Netherlands, supplemental lighting sources may be needed from October until February. The current standard supplement of the light source in greenhouses is High-pressure sodium (HPS) lights which, however, have an inefficient conversion rate (30%) of electricity into useful light [14]. The remaining energy is emitted as heat, which can provide 25–40% of the greenhouse heating requirements during the winter months, but is impractical for indoor growing. However, LED lights have emerged as more sustainable and efficient solutions, using up to 80% less energy compared to HPS, thus, reducing operation and energy costs (Fig. 10) [14]. For this reason, using LEDs in the rooftop greenhouses would be recommended.

Fig. 10: Comparison of LED and HPS lighting technologies

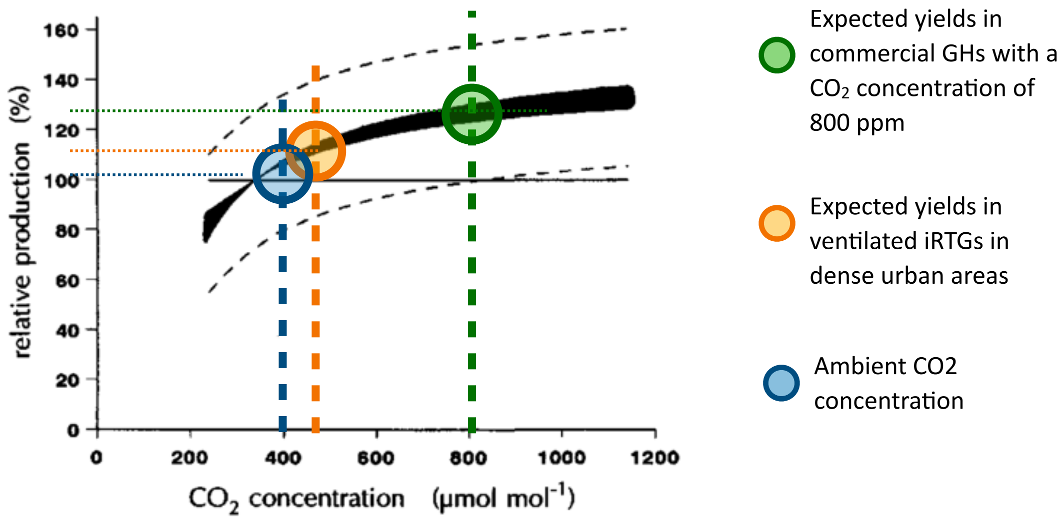


Source: *Proksch, Gundula. (2017). Creating Urban Agricultural Systems: An Integrated Approach to Design. Routledge, New York. [14]*

6. Finally, another important aspect that affects the production capacity in greenhouses is CO_2 enrichment [18]. This process consists of increasing the concentration of CO_2 within the growing enclosure, implementing plants' photosynthesis, thus obtaining a much higher crop yield. The higher is the carbon concentration in the greenhouse, the more efficient becomes the photosynthesis process [17]. Conventionally, growers increase the CO_2 concentration in greenhouses by releasing compressed food-grade CO_2 from tanks or by burning natural or propane gas. However, in a highly dense urban environment, it is counterproductive to burn gas or fossil fuel for CO_2 fertilization, while sustainability goals require increased CO_2 sequestration [14]. The enriched concentration of CO_2 in commercial greenhouses is generally around 800 ppm [19]. Under 200 ppm plants do not have enough CO_2 to start the photosynthesis, while with a quantity higher than 2000 ppm, the concentration of CO_2 becomes toxic for plants [18]. At 800 ppm concentration, the increasing yield factor is 120% considering a 100% yield when plants are grown at an ambient concentration of 410 ppm [20]. Thus, the amount of CO_2 contained in the outside air is sufficient for plants to grow and that can be provided by natural ventilation. However, when greenhouses are sealed during the winter months, CO_2 levels will drop as plants use them during photosynthesis. Indeed, in the

absence of ventilation, the levels of CO_2 concentration the greenhouse rapidly drop until 150 - 260 ppm, highly compromising the production of biomass. In this sense, new researches [17] have investigated the possibility to use the residual air from the building to enhance crop production, avoiding CO_2 enrichment [17]. Results reported by the scientists at the ICTA building in Barcelona show that recirculating CO_2 from the building into the greenhouse could guarantee a constant concentration of 450 ppm [17], providing optimal conditions for plant's growth. However, the experiment was conducted in an office building, where most of human CO_2 emissions happen during the day. In residential buildings, CO_2 flows might be different compared to office buildings, considering that the highest CO_2 concentrations happen at night [21]. Thus, further research concerning the possibility to use exhaust air from the residential buildings and pump it into the integrated greenhouse system is needed. For the purpose of this research, however, indoor CO_2 concentrations in the greenhouse were assumed to be 450 ppm, coherently with the literature review. This assuming that CO_2 enrichment processes would not be integrated in the rooftop greenhouse production. In this sense, it is to assume that the production capacity in the rooftop ventilated greenhouses is lower compared to the commercial greenhouses that were taken as a reference to evaluate the productivity of the crops. Looking at Fig. 11, it is possible to estimate crops' average loss in productivity is around 15-20%.

Fig. 11: Different yields based on CO2 concentrations



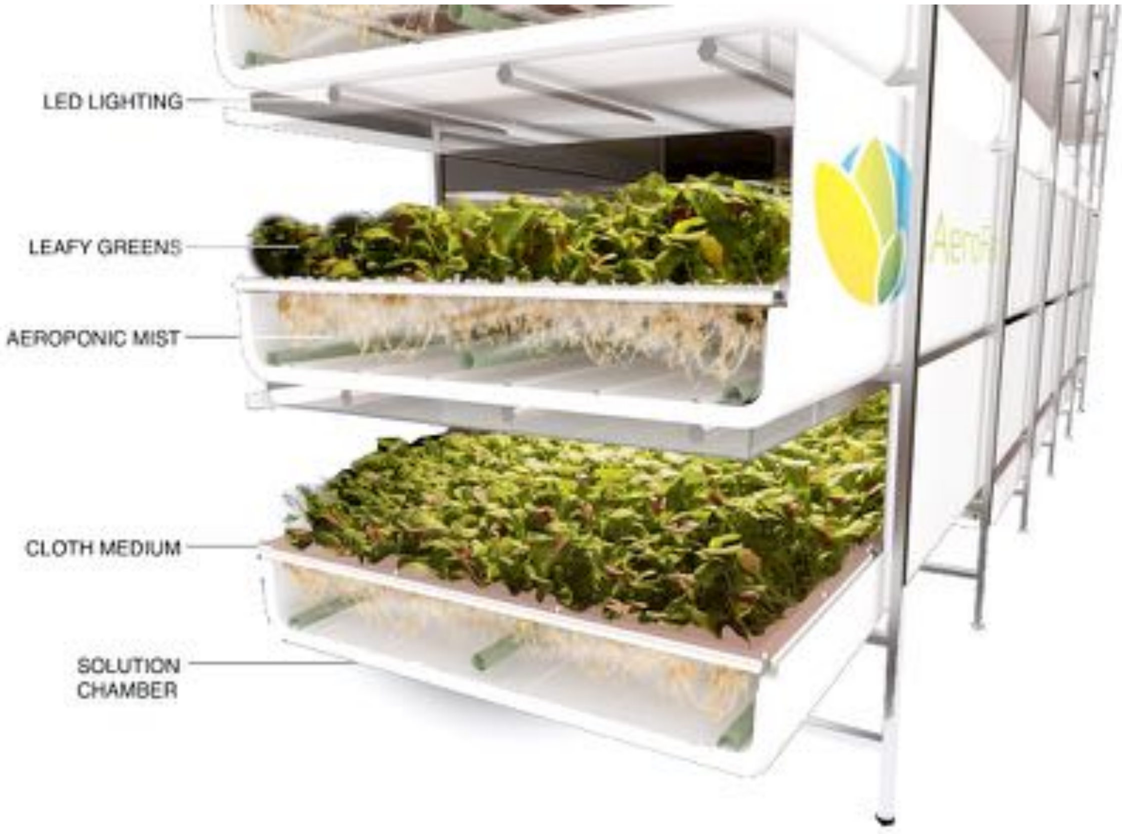
Source: *Nederhoff, E.M., (1994). Effects of CO2 concentration on photosynthesis, transpiration and production of greenhouse fruit vegetable crops. Horticultural Supply Chains, PE&RC. [18]*

While the set-ups for iRTGs can benefit from passive systems to enhance plants' growth, in indoor facilities the inputs for production must be generated artificially. Indeed, plant factories are located in air-tight warehouse structure, completely secluded from the external climates. This means that even natural light is forbidden to enter the structure, and it must be substituted by artificial light to start plants' photosynthetic processes. For this reason, this production method is often called Plant Factory with Artificial Lighting (PFAL). Furthermore, all other natural inputs that contribute to plants' growth need to be completely replaced artificially. Thus, specific technologies are required to properly operate plant factories in order to create the favorable conditions to maximize yields:

1. Maximizing yields while dramatically reducing their spacial footprint is the main objective of plant factories. In this regard, plants can be stacked on multi-layers trays, this way, production

per square meter can increase exponentially depending on the number of layers in which plants are cultivated. For this reason, growing methods should have a relatively low weight and require minimum heights. In this sense, growing beds, deep flow technique (DFT) and aeroponic production are the recommended and most used growing methods in plant factories (Fig. 12).

Fig. 12: Example of stacked aeroponic system for plants' growth in the AeroFarm Plant Factory



Credits: *Aerofarm.* https://aerofarms.com/technology/

2. While greenhouses can benefit from natural ventilation, indoor facilities need an automated forced ventilation system. Outdoor ventilation is not encouraged due to the reduction of CO_2 use efficiency and the potential introduction of pests and pathogens from outside [22]. Indeed, within air-tight warehouse facilities, high planting density causes CO_2 concentration to drop below outdoor values, limiting photosynthesis and plant growth (Gómez et al., 2019). Thus, forced ventilation systems use extractor fans that pull exhaust air out of the growing spaces, providing constant optimal levels of ventilation in the warehouse structures.

3. Indoor climate in plant factories is automatically controlled to keep steady indoor temperature and humidity. Indeed, microclimate control management is fundamental to guarantee a proper plant development [23]. The typical airtight structure of plant factories calls for continuous dehumidification to avoid relative humidity level due to evapotranspiration [23]. Dehumidification can be obtained by using heat pumps that manage the climate control [23]. Moreover, temperatures also need to be uniform inside PFALs to obtain uniform growth [22]. In this sense, air fans that can guarantee homogenous air recirculation inside the PFAL are needed [22]. Commonly adopted strategies for dehumidification in PFAL use heat pumps to manage climate control. Both heat pumps and air fans need electricity-energy, whose costs, summed with those consumed by the artificial lighting system were estimated to account for

around the 30% of the total operation costs of a PFAL [24]. In this regard, the use of systems that can maximize energy efficiency are recommended. In a recent article, Yokoyama et al. (2019) [25] reported that conventional heat pump systems can be substituted by co-generation (HVAC) and even tri-generation equipments. Using the latter would, in fact, allow the production of heat, electricity and CO2, saving up 30% of the costs connected to climate control management.

4. In PFALs, electric lighting is used for simulating solar radiation over a light/dark photoperiod of generally 16/8 hours daily [22]. However, supplying PFALs with artificial light is raising concerns on the environmental and economic sustainability of the system [26]. Lighting system, in fact, contributes to 50-55% of the total operating costs of a PFAL [25]. Furthermore, it accounts for almost two third of the total energy consumption [19]. Nonetheless, the technological advances made in the lighting sector developed new solution such as light emitting diodes (LEDs), which resulted in highly versatile and energetically efficient lighting systems for paint cultivation [27]. In indoor conditions it is possible to give plants the best light recipe for growth and development [28]. In this sense, LEDs provide the great opportunity to fulfill the light requirements at any cultivation stage, thanks to their capability to emit light in narrow bandwidths [27]. Furthermore, due to their easy adjustability, LEDs lighting systems enable to modulate the quality, intensity and photoperiod of the emitted radiation, leading to an optimization of plants growth in terms of yield and quality [29]. Accordingly, several researches on the application of LED technology for indoor plant cultivation focused on the study of the effect of red (R) and blue (B) light on growth, morphology and physiological responses of plants or toward the identification of the optimal RB ratio within the spectrum. On the other hand, the most claimed weakness of LED lighting technology is the initial cost [27], which resulted 5 to 10 times higher than HPS lamps (Fig. 10). However, when compared to more traditional lighting systems, the capital investments may be counterbalanced by the longer lifespan and greater efficacy of LEDs.

5. The configuration of PFALs, which makes them secluded from the exterior climate, prevent outer inputs to enter the warehouse structure. In this sense, PFALs are sealed and, as written before, natural ventilation is highly discouraged. In this sense, in absence of natural ventilation, the high density of plants contained in PFALs rapidly absorb all the CO_2 present in the environment, causing a quick drop in CO_2 concentration that would impede plants' photosynthesis. In this regard, the only way to keep optimal CO_2 levels inside the PFAL is with CO_2 enrichment processes. They can be generated by the tri-generation system, together with electricity and heating [25], or through the burning process of natural gas in a gas tank. CO_2 enrichment allows to keep a constant carbon dioxide concentration to 800 ppm through the whole stages of production.

In conclusion, with regards to iRTGs, it is important to balance between the technologies that can maximize production, reducing the spatial footprint of the hydroponic system, and the passive systems that will allow a lower consumption of resources. This, keeping in mind that urban food production needs to respect and protect people's health, increasing the sustainability of local food systems. Thus, it is highly recommendable in dense urban areas to maximize the interactions between the building and the production systems, taking advantage of passive solutions for energy generation and CO2 enrichment. In this sense, this research specifically aimed at maximizing water and nutrient flows interactions between the building and the off-soil production systems. However, further research on the integration of other relations between buildings and production systems is necessary to optimize even more food production in BIA, complementing the research developed in this thesis. On the other hand, PFALs rely primarily on mechanical systems, which make them independent from external climate conditions. To be viable, PFALs need to properly integrate the most advanced lighting, hydroponic, and climate control technologies, as their cost can only be justified by a higher production that maximize land surface efficiency, reducing the energy inputs required to produce 1 kg of fresh weight produce [23].

3.2 Step 1: Choosing the crops. General and site specific considerations

Fruits and vegetables are important elements of a healthy, balanced diets, bringing us vitamins, minerals, fibers, and some energy (in form of sugar). Epidemiological studies have shown that high intakes of fruit and vegetables are associated with a lower risk of chronic cardiovascular diseases [30] and certain cancers [31]. As UF is unable to provide the city with all its food needs [32], choosing those crops that can provide the maximum nutrients intake and promote healthy diets could be an important criterion in choosing the plants that will be cultivated in the city. However, not all crops are suitable for hydroponic production, while others may not fit local diets, consumers' preferences, or market demand. Thus, when choosing the crops for specific urban areas in a specific context, it will be important to compare the most nutrient crops with local criteria for urban production. Providing fresh fruits and vegetables to an increasingly urban population is key to promote the transition towards healthy, plant-based diets, boosting the consumption of fruits and vegetables in urban areas. Indeed, increased consumption of fruits and vegetables can lead to several health benefits for the urban population. New researches indicated a minimum of 400g of fruit and vegetable per day [33]. However, in 2017 European Heart Network (EHN) paper on "Transforming European food and drink policies for cardiovascular health" calls for an intermediate population goal of more than 400g/day, setting a long term goal of more than 600g/day intake of fruits and vegetables [34].

These recommendations are strictly connected to some important Sustainable Development Goals (SDGs) such as:

- **SDG 2**, which aims to achieve improved nutrition by 2030
- **SDG 3.4**, which aims to reduce by one-third premature mortality from NCDs through prevention, treatment, and promotion of mental health and wellbeing
- **SDG 12.8**, which is to ensure awareness of sustainable development and lifestyles

Nonetheless, despite these recommendations and the proven link between vegetables and fruit consumption with health, in Europe, still most of the countries show an average intake lower than 300 grams a day. Willpower is the most commonly reported perceived barrier to consumption, followed by price and hedonic [35]; it has been noted that better-educated adults show higher vegetable consumption [35]. In this scenario, it emerges the need to improve policies favoring vegetables and fruit consumption in European countries [34], creating a healthy food environment by:

- Promoting national policies and investment plans (including trade, food, and agricultural policies) to favor healthy diets and protect public health;

- Encouraging consumer demand for healthy foods and meals improving their food education.

Thus, it became clear that consumption trends will only change with additional multi-level and multi-sectoral approaches. Best practices must be used for communicating the benefits of fresh fruit and vegetable consumption to those who do not consume the recommended level. This includes changes in policy coupled with changes within the fresh produce sector itself, including marketing and advertising measures, fiscal incentives, and creating healthier retail and public institution food environments [36]. To this concern, integrating food production within new urban developments, as well as in retrofitting projects, might encourage people to implement vegetable and fruit consumption in their diets, functioning as an educational tool towards more sustainable production practices and healthier diets. This strategy is coherent with the new food policies promoted by cities like Amsterdam and London [37, 38], where UF initiatives are crucial in bringing fruits and vegetables to the center of everyday diets, aiming at reaching the future consumption goal of 600 grams/person per day of fruits and vegetables.

However, not only the quantity but also the quality of consumed crops in urban areas is fundamental to guarantee access to healthy food to local communities. In this sense, it is important to identify and select crops that will guarantee maximum nutrients intake. The problem is that people don't exactly eat nutrients, but food that contains nutrients. In this regard, the best course of action identified by the FAO and the WHO is to provide governments and consumers with guidelines that suggest what food best fits local dietary patterns, and that can highly improve everyday diets. These indications are provided by the EU in the form of the Food-Based Dietary Guidelines (FBDGs) [39]. They are an instrument and an expression of food and nutrition policy, which primary purpose is to educate healthcare professionals and consumers about health promotion and disease prevention. FBDGs are science-based recommendations translated in the form of guidelines for healthy eating [39]. They are primarily intended to inform consumers, and as such, they are tailored for a specific region or country. Determining nutrients intake goals is the first step for the development of FBDGs, focusing on how a combination of foods can meet nutrient requirements. Dietary guidelines represent the practical way to reach the nutritional goals for a given population. They take into account customary dietary patterns and indicate what aspects of each should be modified. They consider the ecological setting in which the population lives, as well as the socioeconomic and cultural factors that affect nutritional adequacy.

Thus, consulting local FBDGs is an important step when choosing crops for urban food production in a specific context. For instance, considering that the proposed project is located in Amsterdam, Dutch FBDGs provide insightful indications about the food patterns that should be followed by Dutch people. In concert with the Amsterdam food policies, Dutch FBDGs propagate a shift into the direction of plant food [40]. In this regard, the final report of the Dutch guidelines advises eating at least 200 grams of vegetables and at least 200 grams of fruit daily. Hence, the inclusion of foods in the diet which has high micronutrient density, such as pulses or legumes, vegetables, and fruits, is the preferred way of ensuring optimal nutrition, including micronutrient adequacy, for most population groups. Adding the minimum recommended amounts of these foods will add micronutrient density to the staple diet and in doing so it could reduce the prevalence of diseases resulting from a micronutrient deficiency across population groups [39].

Therefore, dietary diversification is important to improve the intake of critical nutrients. According to the FAO-WHO joint Consultation [41], five micronutrients are considered to be of public health relevance or serve as markers for overall micronutrient intake: Vitamin A, Vitamin C, Folate, Iron, and Zinc. These nutrients are so important as they are among the most difficult to obtain in cereal and tuber-based diets. The proper integration of these five micronutrients in common European cereal- and tuber-based diets could enhance nutrients assimilation by the human body. As such, this research analyzed this group of micronutrients and associated to it those foods that can guarantee their maximum uptake:

- *Vitamin A:* Vitamin A (retinol) is an essential nutrient needed in small amounts by humans for the normal functioning of the visual system; growth and development; and maintenance of epithelial cellular integrity, immune function, and reproduction. Provitamin A carotenoids are found in green leafy vegetables (e.g. spinach, amaranth, and young leaves from various sources), yellow vegetables (e.g. pumpkins, squash, and carrots), and yellow and orange non-citrus fruits (e.g. mangoes, apricots, and papayas).

- *Vitamin C*: Vitamin C (chemical names: ascorbic acid and ascorbate) is a powerful antioxidant. It is water-soluble and is therefore especially found in the aqueous fractions of the cell and body fluids whereas vitamin. Ascorbate is found in many fruits and vegetables. Citrus fruits and juices are particularly rich sources of vitamin C but other fruits including cantaloupe and honeydew melons, cherries, kiwi fruits, mangoes, papaya, strawberries, tangelo, tomatoes, and watermelon also contain variable amounts of vitamin C. Vegetables such as cabbage, broccoli, Brussels sprouts, bean sprouts, cauliflower, kale, mustard greens, red and green peppers, peas, and potatoes may be more important sources of vitamin C than fruits, given that the vegetable supply often extends for longer periods during the year than does the fruit supply. All these foods, when added to a diet or meal in regular portion sizes, will significantly improve the vitamin C density.

- *Folate:* Folate has many functions in the body helping tissues grow and cells work. It works together with vitamin B12 and vitamin C to help the body break down, use, and create new proteins. It helps in the formation of red blood cells and the production of DNA. Folate is found in a wide variety of foods, although it is present in a relatively low density except in the liver. Diets that contain adequate amounts of fresh green vegetables will be good folate sources. The best sources of folate are organ meats, green leafy vegetables, and Brussels sprouts. However, folate losses during harvesting, storage, distribution, and cooking can be considerable.

- *Iron & Zinc:* Minerals such as iron and zinc are found in low amounts in cereal- and tuber-based diets. Therefore, it is not possible to meet the recommended levels of iron in the staple-based diets through a food-based approach unless some meat or fish is included. The consumption of ascorbic acid along with a food rich in iron will enhance iron's absorption. There is a critical balance between enhancers and inhibitors of iron absorption. Nutritional status can be improved significantly by educating households about food preparation practices that minimize the consumption of inhibitors of iron absorption. For zinc, the presence of a small portion (50 g) of fresh food will secure the dietary sufficiency of most staple diets.

After the analysis of these five micronutrients, it became immediately clear that Iron and Zinc won't be provided by vegetable crops, as they are mostly found in meat or other dairy products. For this reason, the research for the most nutrient crops will focus on the content of Vitamin A, Vitamin B, and Folate in fruit and vegetable. To this concern, Table 3 present a summary of the crops that contain high levels of these micronutrients and that can be produced hydroponically based on the indications provided by the Joint FAO/WHO Expert Consultation on Human Vitamin and Mineral Requirements [41]. Concerning their production methods, it is not often clear how to determine which crops can or cannot be grown hydroponically. Recent experiments in Dutch and Spanish greenhouses have demonstrated that almost all sorts of crops could potentially be grown indoor [42]. However, the literature review [43, 44] and the Dutch greenhouse horticulture manual "KWIN" [45] were taken as reference pillars for the determination of which crops can be conveniently grown in hydroponics. Furthermore, once determined the crops that can be cultivated in hydroponics and that have the higher nutrient intakes, it is possible to assign each crop to its specific enclosure based on an extensive literature review [22, 46, 47]. Indeed, as reported in Chapter 2, it is possible to identify two main typologies of enclosures: i) translucent greenhouses, and ii) Plant Factories with Artificial Lightning (PFALs). Following Kozai et al. guidelines [22], crops production methods must be chosen to take into consideration that plants suited to PFALs have the following characteristics [22]:

- short in height (about 30 cm or less) to be adapted to multilayer cultivation racks with a vertical distance between the culture beds of 40–50 cm;
- fast growing (harvestable 10–30 days after transplanting);
- growing well under low light intensity and at high planting density;
- high-value product if fresh, clean, tasty, nutritious, and pesticide-free;
- the product value can be effectively improved by environmental control;
- about 85% in fresh weight of the plant can be sold as produce

On the other hand, plants suited to greenhouses using sunlight rather than PFALs for improved quality and yield include:

- fruit-vegetables such as tomatoes, peppers, and cucumbers that contain large amounts of functional components;

- berries such as strawberries and blueberries;
- high-end flowers such as Phalaenopsis, dwarf loquats;
- mangoes and grapes, etc. for growing in containers with trickle irrigation;
- non-woody or annual medicinal plants such as Angelica, medicinal dwarf Dendrobium, Asian ginseng, saffron, and Swertia japonica.

Table 4: List of crops rich in Vitamin A, C, and Folate associated with their advised hydroponic production methods

Type of crops	Name of the crops	Production method
Fruit	Strawberries , Blackberries, Raspberries.	PFAL / Hydroponic in ventilated greenhouse
	Lemon and Orange trees	Hydroponic in ventilated greenhouse
Tropical Fruit	Papaya, Mango and Kiwi	Soil based greenhouse/ Hydroponic in ventilated greenhouse
Fruit vegetables	Squash and Pumpkin	Hydroponic in ventilated greenhouse
	Tomatoes, Bell Pepper and Cucumbers	Hydroponic in ventilated greenhouse
	Cauliflower	Hydroponic in ventilated greenhouse
Leafy greens	Spinach, Kale & Mustard Greens	PFAL
	Chard, Cabbage, Romain, Bok Choi, Romain	PFAL

Site-specific considerations for corps choice

Table 3 constitutes the ground zero for choosing the crops based on their nutrient intakes in specific urban environments. As urban greenhouses and plant factories don't have the vast dimensions possessed by commercial greenhouses in the countryside or in peri-urban areas, it is highly unlikely that all the crops will be produced in a building or even in a small district. For this reason, a further selection of crops between those listed in Table 3 is necessary to choose the final crops that will be produced in the Sluisbuurt area.

The first criterion for choosing the crops can be identified in dietary guidelines proposed by the local FBDGs [40], dietary patterns and market demand. As previously reported, the only indications about fruit and vegetables provided by Dutch FBDGs concern the minimum consumption:

- 200 grams of vegetable per day per person
- 200 grams of fruit per day per person

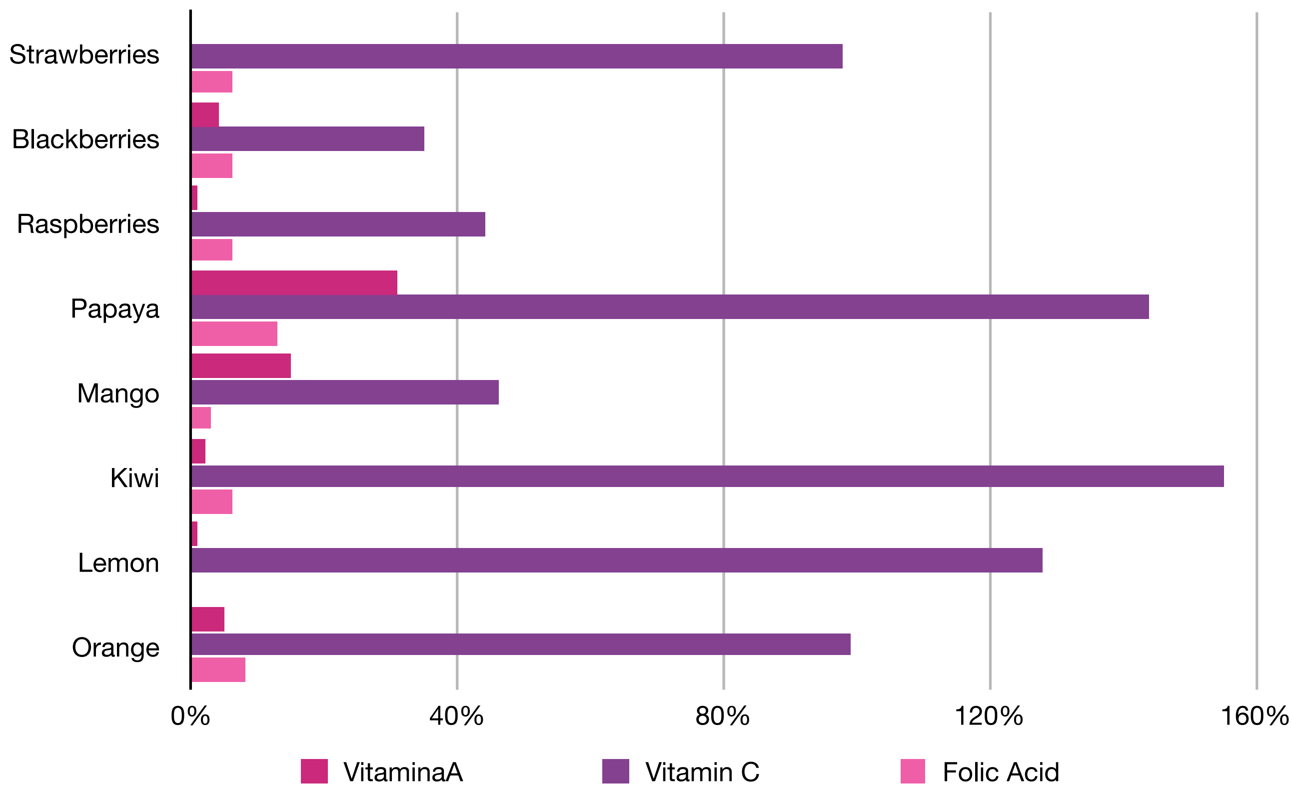
Minimum consumption indications will serve as inputs when assessing the dimension of the production spaces. Based on these indications it is already possible to assume that half of the production will be dedicated to vegetable production and the other half to fruit production. However, dietary guidelines do not give any more informations regarding dietary preferences and habits that would help guiding the final choice. In this regard, it must be taken into consideration that in high populated metropolitan cities, where several cultures live, dietary patterns have changed over the years and food cultural contamination has highly influenced the local diets [35]. Thus, choosing crops based on dietary patterns in highly dense, inclusive, and multicultural cities might not be possible nor recommendable.

A second criterion that may prove useful to make the final choice is to compare the selected crops with those that are most produced in surrounding area. For instance, most of the production of fruit and vegetables in the Netherlands is already happening in greenhouses.

Choosing the same crops, like tomatoes, that are already highly produced indoor may constitute an advantage, as the technology and the knowledge over production are already developed. However, it could also constitute a disadvantage as the market will be saturated with cheaper produce coming from intensive productive greenhouses. During the analysis of the state-of-the-art sheets in Chapter 2, it was studied how a rooftop greenhouse in Den Haag (NL) went bankrupt due to its difficulties in growing and commercializing tomatoes and fruiting crops in a relatively small urban farm next to a global leader in tomato production, known as Westland. In this sense the choice of crops is crucial for marketing purposes, and differentiate the production (i.e. strawberries and blueberries instead of tomatoes and cucumbers [48]) will make the difference between a possibly successful project and another one who's destined to fail. In this regard, before planning and designing BIA projects, it is important to clarify the objectives of the integrated food production. Considering that the objective of BIA districts would be creating a food community with no marketing purposes, a comparison with other intensive production areas in the surroundings will not be considered an issue.

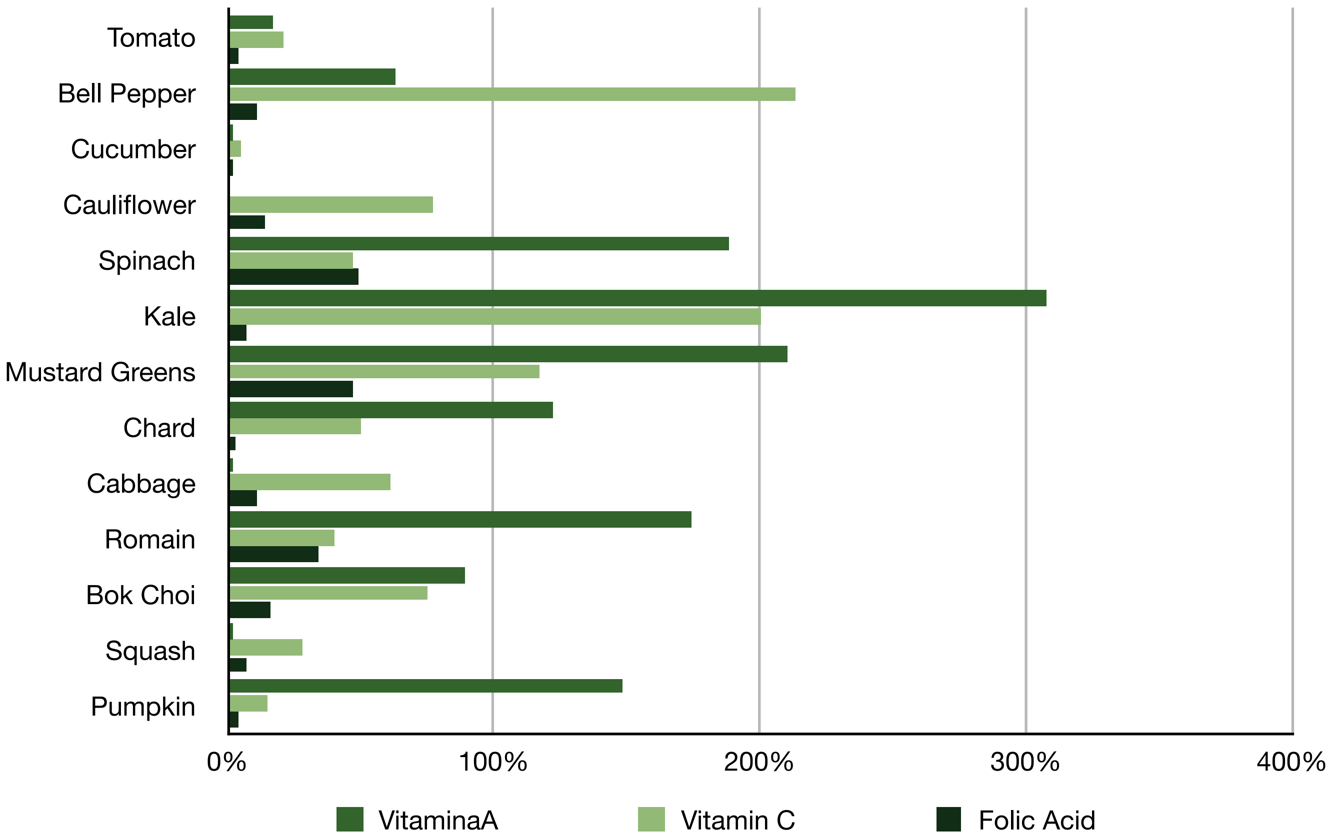
Finally, a third criterion for the choice of the crops consists in a more in-depth analysis of each crop, determining the specific content of Vitamin A, C, and Folate based on their percentage daily value[1]. The analysis was conducted by reporting and comparing data from the Food Data Central of the United States Department of Agriculture -USDA - referred to the year 2019 [49]; and from the Joint FAO/WHO Expert Consultation on Human Vitamin and Mineral Requirements [41]. The results were then compared and reported below in Figures 13A and 13B. The objective of this analysis is to see if there are crops that have higher contents of Vitamin A, C and Folate and thus, provide a better nutrient intake in urban environments where a lower production is expected.

Fig. 13A: Fruits Percent Daily Value per 100 g of produce



[1] The %DV shows how much a nutrient in a serving of a food contributes to a total daily diet. The %DV helps you determine if a serving of food is high or low in a nutrient.

Fig. 13B: Vegetable Percent Daily Value per 100 g of produce



From the charts it clearly emerged that the selected fruit crops are rich in Vitamin C, while in the vegetable the predominant component is Vitamin A. As expected, folic acid is present in a low content in both fruit and vegetable. One interesting outputs coming from this analysis is that certain crops have higher content of micronutrients than others. Thus, if the objective of food production is to improve healthy diets in local communities, other than experimenting hydroponic wastewater recovery in urban areas, the most logical choice is to produce those crops that can guarantee maximum intakes of micronutrients. Some crops, like papaya, mango, pumpkin, and citrus trees were not considered relevant for hydroponic production even if they are rich in micronutrients. This is because these crops require greater spaces to grow compared to those that could be found in urban areas. Furthermore, as they are tree crops, it would require them at least three years to fully mature and be available for the local population. Thus, excluding these crops, three macro-categories were considered optimal for urban food production in this particular case-study:

Fruit - Berries: Strawberry, Raspberry, and Blackberry. They have moderate to high content of Vitamin C, while Raspberries have the higher content of folic acid. For practical reasons and supported by the literature review and field experiments conducted at the PFAL pilot plant in Bologna [46], these three crops were assigned the same yield performances and production characteristics as shown in Table 5.

Fruits Vegetables: Tomato and Bell peppers. Eventually, for the purpose of this research, cucumbers were not taken into consideration as they showed the lowest quantity of micronutrients. For practicality reasons and supported by the literature review and the field experiment conducted in Spain and in Dutch Venlo greenhouses [50], tomatoes and peppers were assigned an average yield performance and same production characteristics has shown in Table 5.

Leafy greens: They have the highest content of Vitamin A and Folic Acid. They are short cycle crops, perfect to be grown in PFALs. Similar to the other two macro-categories, for practicality and supported by the literature and field experiments conducted at the University of Bologna [47, 51], all leafy greens were assigned the same average yield performance and same production characteristics has shown in Table 5.

Due to the different number of annual production cycles and the growing requirements, it was decided to assess the productivity of the crops in g/m2 per day. Water requirements were calculate based on the references found in literature.

Tab. 5: Expected yields, nutrients and water requirements of the selected macro-categories of crops

	Berries	Fruit Vegetables	Leafy greens
Production method	PFAL on 5 levels trays.	Ventilated rooftop greenhouse	PFAL on 5 levels trays.
Expected yields (g/day/m2)	135 [46]	110* [50]	1000 [51]
Water use efficiency WUE (g FW /L H_2O)	35 [46]	71 [50]	80 [51]
Water recovery from dehumidification	76% [51]	NA	76% [51]
Water requirements (L/m2 day)	3,86 [46]	1,55 [50]	12,5 [51]
Nutrients requirement (Composition of the nutrient solution)	N-NO_3^-= 6mM [46] PO_4^{3-}= 3mM [46] K+= 4mM [46]	N - NO3- = 21,1 mM [52] P - H_2PO_4 = 1,56 mM [52] K = 10,8 mM [52]	N-NO3− = 12.4 mM [53] P = 1.1 mM [53] K: 7.2 mM [53]

* The production capacity of the Fruit Vegetable in the cited literature and referred to Tomatoes' yields in Dutch greenhouses [50] is actually higher than the one reported in this table. However, due to the utilization of urine as fertilizer and the limited dimension of the rooftop greenhouses, the cited yield was reduced by a 30%. This reduction is consistent with the findings of Shirly Tentile M. Et al. (2020), reported in Chapter 4.

3.3 Step 2: Assessing the production capacity of the system

Knowing the production capacity of the crops and their production methods is crucial to determine their spatial requirements, as well as to assess wether or not the demand of fruit and vegetable can be satisfied by the designed production systems. To do so, it was written a simple equation that put in correlation the number of inhabitants with the expected food demand and the production capacity of the systems concerning a specific crop:

$$D = \frac{Sp \cdot \overline{p} \frac{g}{m^2 \cdot day}}{\sum_{i=1}^{n} I \cdot C \frac{g}{p \cdot day}}$$

This equation represents the ratio between the total production of a certain area (multiplying total surface area times the production capacity of a specific crop) and the expected consumption that will take place in the same area (obtained by multiplying the total number of inhabitants by the expected consumption per capita).

Therefore, the data of the equation are explained as follow:

- ***D*** is the total food demand. Per ***D=1***, 100% of the total demand of a certain crop is satisfied

- ***Sp*** in the total surface of the production space for a determined crop, expressed in m^2

- $\bar{p}$ is a known and represents the expected average production capacity of the selected crops, expressed in grams/m^2/day

- ***C*** is a known data and represents the desirable consumption of certain fruits and vegetables per capita. The total expected consumption must fit in the range of 400 – 600 g/person per day, as suggested by the national FBDGs and international targets regarding fruit and vegetable consumption.

- $\sum_{i=1}^{n} i$ is a known data and represents the total number of inhabitants living in the targeted urban area.

If the goal is set to satisfy 100% of the food demand, all the data are known except for the required dimensions of the production spaces "***Sp*"*.** Therefore:

$$Sp = \frac{\sum_{i=1}^{n} I \cdot C \frac{g}{p \cdot day}}{p \frac{g}{m^2 \cdot day}}$$

Assessing the potential production capacity of Cluster 2 in the Sluisbuurt

As written in the first section of this Chapter, this research will verify the feasibility of a BIA model for cluster 2 of the Sluisbuurt development project. Inputs data coming from the developing plan indicate that:

- The area of intervention is approximately 2 ha
- The total number of dwellings is 390
- Net max housing surface is 13000 m^2 GFA
- Apartment buildings height 20
- Towers host the office spaces and won't be considered in the calculation for the total food demand, nor for the quantity and quality of wastewater produced. However, towers' roofs are taken into consideration for positioning the solar panels, as they can catch the highest solar radiation. Towers height is between 35 and 50 m.

- Apartment surface between 25 m² to 120 m²
- The minimum expected consumption of fruit and vegetable is 400 g/day per capita

Considering an average occupancy of 2/2.2 people per household [8], the total expected inhabitants of the cluster would be in a range between 780 and 860 divided into five building blocks. Keeping the total expected consumption to the minimum requirements of 400 g/person per day, of which 200g of fruit and 200g of vegetable, it is possible to expect a total demand of (400 x 860) 340.000 g/day. Considering the recommendation of national FBDGs [40], 50% of the demand would be for fruit crops and the other 50% for vegetable crops. Moreover, further indications on how to subdivide the production of the vegetable crops are provided by the document "The Dutch diet" written by the national institute for Public Health and Environment [54]. Here, it is reported that 36% of the total vegetable consumption is constituted by fruiting crops; 38% is constituted by leafy greens including salad and cabbage, and 9% is constituted by root vegetables such as carrots and parsnip. The remaining percentage (17%) is represented by mushrooms, stalk vegetables, onions garlic and leek, and other types of grain. Thus, based on this set of data, it is possible to estimate the percentage of consumption related to fruit and vegetable:

- **Fruits: 50%** - All berries. Expected consumption: 200 g/day

- **Vegetable: 50%** of which 55% Leafy greens including cabbage and Romain and 45% Fruit vegetables. Expected consumption of Leafy greens: 110 g/day; Expected consumption Fruit Vegetable: 90 g/day.

Given these inputs, it is possible to create a preferable production scenario calculating the total amount of occupied equivalent productive land required to satisfy the daily demand. Results are shown in Table of 6a and 6b:

Tab. 6a :Total hydroponic production space requirements per crop

Location	**Crop**	**Production capacity (g/m² day)**	**Inhabitants**	**Estimated daily consumption g/p/ day)**	**Minimum cultivated surface m²**
Cluster 2	Fruit	27,0	860	200	6370
	Fruit Vegetables	110,0	860	90	704
	Leafy greens	200	860	110	473
	Total	//	860	400	**7547**

Thus, based on calculations shown in Table 6a, the minimum required cultivated surface is:

- 704 m² of greenhouse production for Fruit Vegetable.
- 473 m² total cultivated surface of PFAL production for Leafy Greens
- 6370 m² total cultivated surface of PFAL production for Berries.

However, the advantage of the PFAL is the possibility to stack the cultivated surface on multiple layers. The hypothesis made for this research is consistent with the model designed by Graamans et al. [19] and consider the production divided into 5-layers trays. This way, the total relative floor space area occupied by the PFALs (showed in Tab. 6b) is respectively:

- 1274 m² for the Berries
- 95 m² for the Leafy Greens.

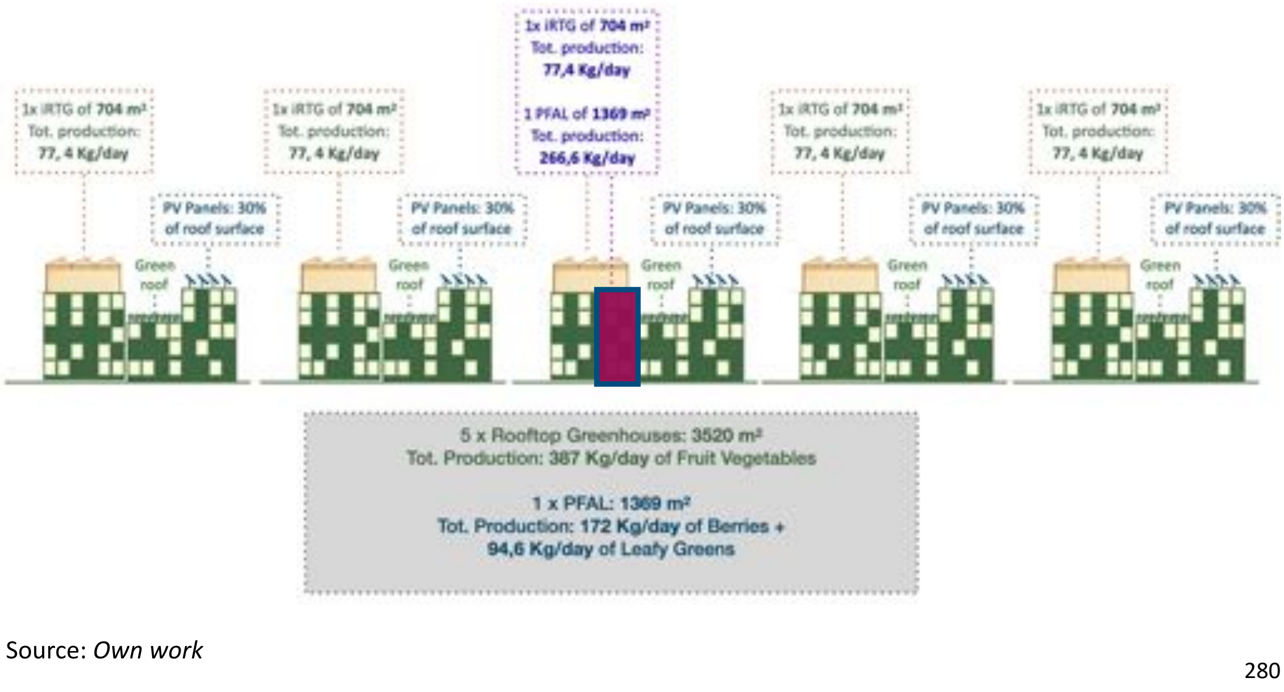
Tab. 6b:Total hydroponic production space requirement per production method

Location	Method	Total production (g/day)	Inhabitants	Required production (g/p/day)	Minimum occupied floor space area m²
Cluster 2	PFAL Berries	172000	860	200	1274
	PFAL Leafy greens	94600	860	110	95
	Rooftop greenhouse	77400	860	90	704
	Total	**344000**	860	400	**2073**

Thus, complying with national indications and considering local diet patterns, the total surface required for production excluding technical and connection spaces is 2073 m². Of the total required surface, 1369 m² are destined for PFALs while 704 m² to rooftop greenhouse (RTG) production.

Concerning PFALs, the total required surface could theoretically be spread over the building blocks that compose the Cluster. In this case, each block should host around 275 m² of cultivated indoor production. However, setting up costs regarding the necessary installation to operate each single PFAL would be higher if the indoor production is scattered. For this reason, it seems more logic to concentrate the whole indoor production in a unique facility in one of the 5 building blocks. This way, only one co-generation system and one CO_2 gas tank would need to be installed. Thus, considering that each apartment building is 5 floor height, the PFAL would occupy a surface of 275 m² each floor. Regarding RTG, the total rooftop surface is 1.3 ha, with an average of 2600 m² roof surface for each building. According to the plan's requirements, 30% of the whole rooftop surface is destined for solar energy production (3900 m²), and another 30% is reserved for green roofs. Thus, a total of 5200 m² can be occupied by RTGs within the entire cluster (an average of 1040 m² on each building). Therefore, if an iRTG of 704 m² is installed on every building block of the cluster, the production of Fruit Vegetables can increase five times (Fig. 14).

Fig. 14: Conceptual configuration of the preferable production scenario of Cluster 2



Source: *Own work*

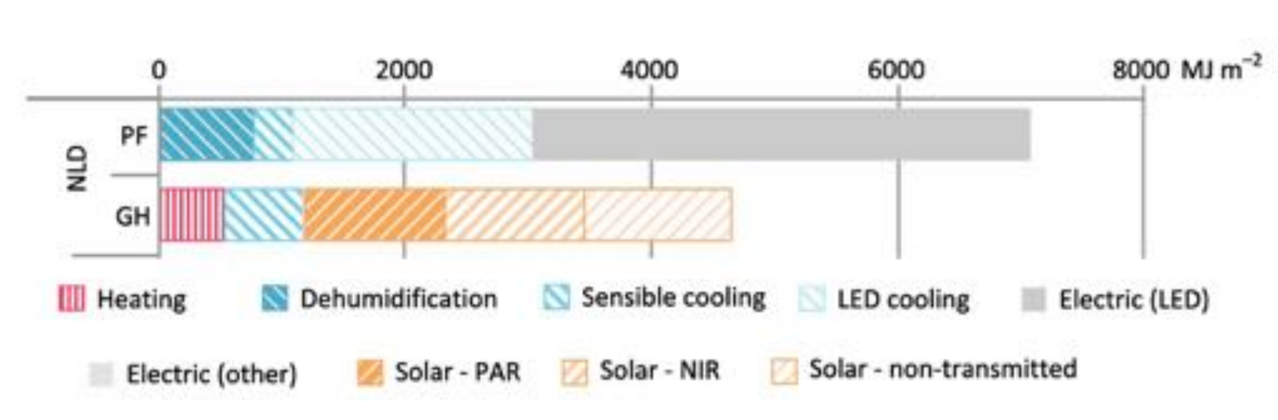
In this scenario, the total production of Fruit Vegetables would be 387.000 g/day. Keeping the same PFAL dimensions, a total production of 653.600 g/day can be expected. Thus, comparing the final production with the initial demand (340.000 g/day), it emerges that the whole Cluster could potentially produce twice as much the food it needs (in terms of vegetable and fruit). This means that, if half of the Clusters of the Sluisbuurt were designed to integrate food production, it would only need 5 of them to feed the district with this set of crops.

Looking on a larger scale, given the new regulations of the Amsterdam plan provided by the Structure Vision 2040 [9], 1 ha with a density of 150-200 households could produce approximately 325 kg/day of fresh produce, providing fruit and vegetable for an equivalent area of 1.9 hectares. However, it was noted that more than 50% of the total production surface is destined to berries. Indeed berries showed a lower production capacity compared to the other crops, although, further research should be done on the efficiency of producing berries in indoor facilities as the number used for this thesis are estimated on the experiments done in the pilot vertical farm recently installed at the University of Bologna [51]. Therefore, due to the high spatial requirements of berries in the PFAL, it was decided to calculate and compare the energy demand of both the PFAL and the Greenhouse to assess the sustainability of the system.

Assessing the energy efficiency of Berries production in the PFAL

As demonstrated by the calculations previously shown in this section, it is required a relatively small spatial footprint for Fruit Vegetable and Leafy Greens to satisfy the local food demand. This allowed to increase production by occupying almost all available rooftop surfaces with ventilated greenhouses. On the other hand, berries production required a higher demand of space, which limited the expansion of the PFAL. Indeed, as demonstrated by Graamans et al. [19], compared to a traditional Dutch greenhouses, a PFAL would require almost seven times more energy to operate (Fig. 15). For this reason, it is recommended to keep the PFAL size limited to the required dimensions needed to satisfy the expected food demand. In this sense, the introduction of PFALs in BIA must be considered carefully. If it is true that PFALs consistently contribute to food production, providing higher yields and an important diversification in the produced crops, it has also been here demonstrated that greenhouse production alone, even without CO_2 enrichment, is able to provide 100% of the total food demand based on the minimum requirements of 400 g/d/person.

Fig. 15: Energy load. A comparison between a plant factory and a greenhouse in the NL



Abbreviation: PAR - Photosynthetically active solar radiation entering the facility; NIR - Near-infrared solar radiation
Source: *Graamans, Luuk & Baeza, Esteban & Dobbelsteen, Andy & Tsafaras, Ilias & Stanghellini, Cecilia. (2017). Plant factories versus greenhouses: Comparison of resource use efficiency. Agricultural Systems. 160. 10.1016/j.agsy.2017.11.003. [32]*

Based on the model developed by Graamans et al. [19], it would require 7000 Mj/m^2 year^{-1} to operate a PFAL similar to the one described for this project. However, 55% of the total energy requirements of a PFAL is determined by lighting only [47]. In order to calculate the total amount of energy needed for lighting the PFAL, the total cultivated surface (showed in Tab. 6a) needs to be multiplied by the required electricity inputs. On the other hand, the energy needed for heating and cooling the PFAL is calculated only on the spatial footprint of the PFAL, considering that crops are cultivated on five-layers trays. To better explain the calculations, the data required to assess the total energy demand were reported in Table 7a and 7b:

Tab. 7a: Energy requirements for LED lights in the PFALs

Parameters	PFAL Berries	PFAL Leafy greens
Cultivated surface	6370	473
Energy required for lighting (MJ/m^2 year $^{-1}$)	3850	3850
Total energy required for lighting (MJ year $^{-1}$)	24525925,9	1821050,0
Total energy required for lighting (KWh year $^{-1}$)	6813302,2	505887,7
Total energy required for lighting (KWh day $^{-1}$)	**18666,6**	**1386,0**

Tab. 7b: Energy requirements for heating and cooling in the PFALs

Parameters	PFAL Berries	PFAL Leafy greens
Cultivated surface *	1274	95
Energy required for lighting (MJ/m^2 year $^{-1}$)	3150	3150
Total energy required for lighting (MJ year $^{-1}$)	4013100,0	299250,0
Total energy required for lighting (KWh year $^{-1}$)	1114839,2	83131,7
Total energy required for lighting (KWh day $^{-1}$)	**3054,4**	**227,8**

* The cultivated surface considered for heating and cooling calculations vary compared to the one used for lighting calculations as it considers the energy required to heat or cool down a room where the production of berries and leafy greens is stacked on 5 layers trays.

Thus, considering the calculations shown in Table 7a and 7b, the total energy demand for heating, cooling and lighting in the two PFALs is respectively:

- PFAL Berries: **21.721 KWh/day**
- PFAL Leafy Green: **1.614 KWh/day**

Considering that a total rooftop surface of 3.900 m^2 is destined to Photovoltaic Panels (PV), the total solar energy production would amount to 1778 KWh/d (see Annex 1 for calculations). As expected, the PFAL for berries is high energy consuming compared to its effective production, more than 12 times higher than the amount of energy produced by the PV panels. Furthermore, it is possible to compare the equivalent energy costs of berry and leafy greens crops with the actual retail price (Table 8).

Tab. 8: Equivalent energy cost per each PFAL crop

Parameter	PFAL Berries	PFAL Leafy Greens
Total energy demand (KWh/day)	21721	1614
Energy costs (€ per KWh) [55]	0,22	0,22
Total energy costs (€/day)	4778,6	355,1
Total daily production (Kg/day)	172	94,6
Equivalent energy costs for the crop (€ per Kg)	27,8	3,8
Retail price of the crop (€ per Kg) [56] [57]	7,38	3,73
Net energy cost of the crops	**-20,4**	-0,0

To confirm the fact that the production of berries in the PFAL is not sustainable, the calculation of the equivalent energy costs of the crop demonstrated that each Kg of berries produced in the PFAL would cost 20,4 € more compared to the current retail price. This can also be explained as there is limited literature now concerning the production of berries in PFALs, and further research might find more sustainable and productive ways to produce berries in indoor facilities. On the other hand, the costs of producing Leafy Greens in the PFAL is approximately equivalent to the retail price. The energetic calculations made in this section of the research calls for a reconsideration of the production systems. In this sense, berries could be produced in rooftop greenhouses, similarly to Fruit Vegetables. However, producing berries in the RTGs would require almost all the total available roof surface. Indeed, considering that the total available rooftop surface is 5200 m^2, it would require 5029 m^2 to produce the berries in the iRTG. This, considering a total production capacity of 34,2 g/day for berries [45], typical of highly efficient high-tech Dutch greenhouse. Thus, producing berries would impede the production of Fruit Vegetables in the neighborhood.

Developing a new sustainable scenario for crops production in Cluster 2

Based on the energetic considerations reported above, it was finally decided to let go of Berries production and focus only on Leafy Greens and Fruit Vegetables. This is expected to have an impact on the overall sustainability of the system, reducing the energy consumption. The new scenario would then produce Leafy Greens and Fruit Vegetables to satisfy the expected food demand of 400 g/person/day [40]. Thus the targeted production will follow the indications provided by the document “The Dutch diet” [54] previously cited, and will be subdivided as follow:

- Leafy Greens: **220 g/person/day**
- Fruit Vegetables: **180 g/person/day**

Therefore, by eliminating berries from the Cluster, it is important to make new calculations assessing the proper spaces for production of the selected crops. Calculations are shown below in Table 9.

Tab. 9 :Total hydroponic production space requirements in the Scenario 2

Location	Crop	Production capacity (g/m² day)	Inhabitants	Estimated daily consumption g/p/day)	Minimum cultivated surface m²
Cluster 2	Fruit Vegetables	110,0	860	180	1407
	Leafy greens	200	860	220	946
	Total	//	860	400	**2353**

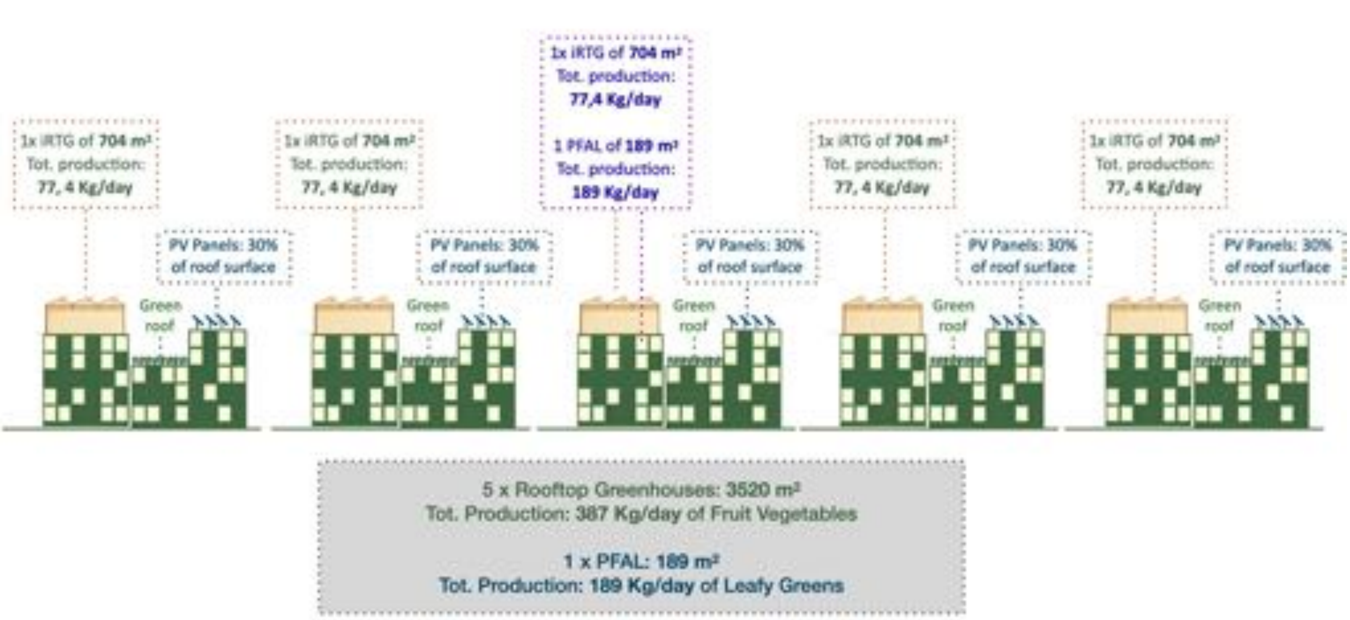
Looking at table 9, it emerges that the minimum area required to satisfy the local food demand of Fruit Vegetable largely fits within the rooftop available surface (5200 m²). Keeping the same settings of the Scenario 1, it would be possible to install a greenhouse of 704 m² on each of the building blocks, considering the needed connective spaces. In this sense, the same production of 387,2 kg/day would be expected. Considering that now the demand of Fruit Vegetables has increased due to the absence of berries and is now 154,8 Kg/day, the rooftop greenhouses produce 2.5 times more than what it is demanded. Concerning the PFAL instead, if the leafy greens are produced on 5-levels trays, the total surface required to cultivate them is 189 m². As shown in Table 10, keeping the dimension of the PFAL to the minimum and enlarging just the production in iRTGs, would produce a total of 576,4 Kg/day of food, which is 160% the initial food demand.

Tab. 10 :Total production of the hydroponic system in the Scenario 2

Location	Crop	Total production (Kg/day)	Expected food demand (Kg/day)	Total occupied floor space area (m²)
Cluster 2	Fruit Vegetables	387,2	155	3520
	Leafy greens	189,2	189	189
	Total	576,4	344	**3709**

Thus, the new scenario would have 5x greenhouse of 704 m², one on each roof, plus 1 PFAL of 189 m² cultivated surface (Fig. 16).

Fig. 16: Conceptual configuration of Scenario 2



Nonetheless, the spatial footprint of the PFAL are expected to be higher, as 189 m² is only the surface required to accommodate all the 5-layers trays. Considering the new PFAL installed at the University of Bologna, it would require an extra 30% of connective and installations spaces to properly operate the PFAL. Thus, the total spatial footprint occupied by the Leafy Greens PFAL in Cluster 2 is estimated to be **245 m²**. Based on the new scenario, it is possible to calculate the new total energy costs and requirements to assess the sustainability and feasibility of the system.

Calculating the energy costs of the Scenario 2

Compared to the Scenario 1, the new production configuration expressed in Scenario 2 requires a much smaller PFAL surface, as Leafy Greens are characterized by a higher production capacity. Considering the PFAL modeled by Graamans et al. [19] and referencing to table 7a and 7b with regards to the energy requirements and relative costs, it is possible to calculate the total equivalent energy costs of the Leafy Greens PFAL considering that all the solar energy produced by the PV rood would integrate the energy requirements of the PFAL (Tab. 11):

Tab. 11: Total energy requirements in the PFAL Leafy Greens and equivalent energy price for the crops

Parameters	**Lighting**	**Heating & Cooling**
Cultivated surface	946	189
Energy required for lighting (MJ/m² year -1)	3850	3150
Total energy required for lighting (MJ year -1)	3642100,0	595350,0
Total energy required for lighting (kWh year -1)	1011775,4	165388,2
Energy requirements (kWh day -1)	**2772,0**	**453,1**
Total energy requirements (kWh day -1)	**3225,1**	
Average solar energy harvesting by the PV (KWh day -1)	1778	
Residual energy needed to power the PFAL (kWh day -1)	**1447,1**	
Energy costs (€ per kWh) [55]	0,22	
Daily energy cost (€/day)	318,4	
Total production (Kg/day)	189	
Equivalent energy cost (€/Kg)	**1,7**	
Retail price of the crop (€/Kg) [56]	**3,73**	
Net energy cost of the crop (€/Kg)	**-2,0**	

Thus, as shown in Table 11, if all the PV energy is given to the PFAL, there will be an actual saving of 2,0 €/Kg for the leafy greens. Thus, an hypothetical family of four that would consume 880 g/day of all sorts of leafy greens, it would save 32,8 € per month and 393,6 per year on the supermarket bill for the leafy greens.

Concerning the iRTGs, the total energy inputs are calculated based on the model developed by Graamans et al. [19]. In the studied model, around 1000 MJ/m² are needed for heating and dehumidification. Plus, for the purpose of this research, the greenhouse modeled by Graamans et al. [19] was integrated with a LED light system in the spectrum of red and blue [47]. Photo/Dark period was considered 8/16 and for a duration of five months (October/February) [14]. The light radiation was calculated based on tomatoes requirements: 300 (µmol $m^{-2} s^{-1}$) [58]. Thus, the total energy required by the LED lamps in the RTGs model developed for this research corresponds to 1.6 MJ/m²/day. This means that the energy required during the winter months by the LED lamps corresponds to 5600 MJ/day, equals to 1555 kWh day $^{-1}$. In the seven months in which LED lights are not necessary, the energy inputs are needed for heating and cooling, and corresponds to 1000 MJ/m² year^{-1}. Thus, considering the total iRTGs surface of 3520 m², the total energy needed for heating and cooling is 365.000 MJ per year (101.390 kWh year^{-1}), approximately 280 kWh day^{-1}.

All this considering, the total energy consumption of the two food production systems compared with the solar energy gain harvested by the PV is illustrated in Table 12 and in Fig. 17:

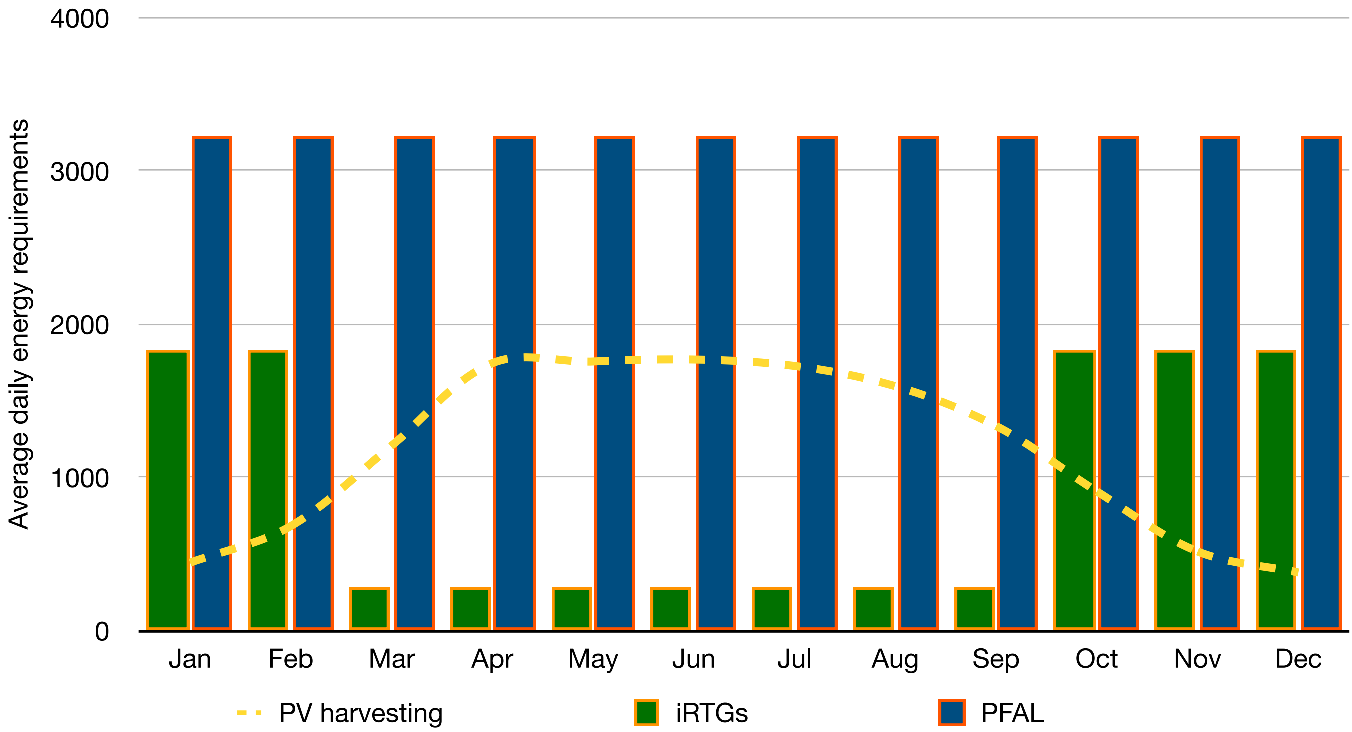
Tab. 12: Average daily energy requirements of the production systems

Period	Average daily sun harvesting by PV panels (kWh/day)*	Rooftop greenhouses energy requirements Av. kWh/day	PFAL energy requirements Av. kWh/day
January	443,7	1835	3225
February	682,0	1835	3225
March	1207,0	280	3225
April	1745,2	280	3225
May	1756,8	280	3225
June	1805,3	280	3225
July	1748,2	280	3225
August	1580,0	280	3225
September	1335,0	280	3225
October	908,9	1835	3225
November	516,8	1835	3225
December	379,3	1835	3225
Average daily energy production and consumption throughout the whole year	**1778**	**928**	**3225**
Daily average energy inputs required from non-renewable energy sources (kWh day $^{-1}$)	**2375**		
Yearly average energy inputs required from non-renewable energy sources (kWh day $^{-1}$)	**866875**		

* Calculated via https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html

Thus, considering the average daily energy demand of 928 KWh day^{-1}, the equivalent energy cost for Fruit Vegetable crops is 204,2 €/day. Considering a total production of 387 Kg/day, the equivalent energy price per kilogram is 0,53 €/Kg [59]. The current retail price for tomatoes is 2,58 €/Kg [59], thus, the final energy savings on the supermarket bill would be 2,55 €/Kg.

Fig. 17: Average daily energy consumption of the iRTGs and the PFAL compared with PV solar energy harvesting



Source: *Own work*

Thus, the final balance of equivalent energy cost per Kilogram of produced crops is 4,1 €/Kg as reported in the summary Table 13.

Tab. 13: Final energy and costs balance of the hydroponic production systems

	PFAL	iRTGs
Average daily energy requirements (net value considering PV solar energy harvesting)	1447,1	928
Energy costs (€/kWh)	0,22	0,22
Daily energy costs (€/day)	318,4	204,2
Total production (Kg/day)	189	387
Equivalent energy cost per Kg of produce (€/Kg)	1,7	0,5
Retail price per Kg of produce (€/Kg)	3,7	2,6
Total saving per Kg of produce (€/Kg)	**2,0**	**2,1**

In conclusions, removing Berries from the Cluster food production had a great impact on the overall sustainability of the system, both economically and environmentally. Nonetheless, even when considering PV solar energy production, the total amount of energy needed from the production systems to operate is 866.875 kWh per year. Considering that the average Dutch households consume 3,100 kWh electricity per year, the energy required by the hydroponic systems to produce food in urban areas is equivalent to the energy needed to power up 280 households. However, comparing the cost of electricity with the cost per Kg of produce, producing crops in urban areas represents a clear economic advantage. In this sense, a more in-depth investigation on other costs related to production such as labor, water and fertilizer costs will be further discussed in this chapter to assess the actual economic advantages of producing food in urban areas.

3.4 Step 3: Assess domestic wastewater characteristics

As people's life is not sedentary and it is moving between home, work, commercial and public domains, so toilet-use patterns are equally dispersed. It can be expected that there is a spatial variance in composition and volume of wastewater across urban areas [60], and that therefore certain locations might be more interesting for recovery via new sanitation systems than others. It is not practicable to calculate exact nutrient excretion for each person in an entire urban population as toilet-use patterns and nutrient concentrations in excreta are based on individual behavioral patterns and diet. Therefore, it is important to assess the average amount of excreta a certain population produces in a determined area and in a specific location. A 2019 study [60] assessed the distribution of Dutch population in time and space:

1. **Home:** Dutch citizens (>12 years old) spend 76% (127.3 hr) of their week at home. The hours spent working from home are not included in this percentage.

2. **Work:** Dutch citizens (>12 years old) spend 12% (19.6 hr) of the week engaged in paid work.

3. **School:** Students between 12 and 18 years of age spend on average 14.8% (24.8 hr) of the week at school. Elementary students in the Netherlands spend a minimum of 7,520 hr in class during their complete elementary education (ages 4–12). This averages to 940 hr year−1. Weekly data is not available for educational facilities.

4. **Out of house activities:** The remaining 13% (20.9 hr) of the week (ages > 12 years old) is spent on other out of house activities. This data was not included because the locations at which these activities took place was unknown.

The same study [60] specified that the frequency of urination is estimated to be six times per day with 60% of total urine volume excreted between 9:00 and 21:00 and the remaining 40% during 21:00–9:00, while feces are expelled circa 1,1 times/day [63]. According to the STOWA report from 1998, the average Dutch person prefers to use the toilet at their home; for urine, 85% is excreted at home and 15% is excreted away from home, while 96% of feces is excreted at home and 4% is excreted away from home. Based on the time-use data, Wielemaker et al. (2019) [60] finally calculated that 72% of urine is excreted at home, and 14% at work. The remaining fraction is excreted during the time spent on activities such as hobbies, sports, and social activities which are difficult to attribute to a specific location. In this context, it makes sense to study the integration of hydroponic systems with residential buildings where most excreta are produced, representing the urban hotspots for resource conversion.

In the previous Chapter it was reported how the installation of new localized, source-separated sanitation systems has permitted to treat and recover resources from different waste-streams of domestic wastewater, minimizing cross-contamination and dilution of streams. For this reason, new sanitation systems are especially interesting for neighborhoods, particularly for new developments or neighborhoods undergoing renovation, fitting perfectly in the new development plan of the Sluisbuurt area. Thus, it was considered that all buildings in Cluster 2 would have installed urine diverting flush toilets for source-separation. Using gravity toilets, 5 L/person/day of flushing from toilets are expected [62]

Based on these considerations, assuming that the whole Cluster 2 would host the maximum number of people (860), it is possible to determine the final composition of Dutch domestic wastewater as reported in Table 14.

Tab. 14: Final composition of domestic wastewater

Parameter	Unit	Urine	Grey Water*	Inhabitants	Unit	Urine composition	Greywater composition
Volume	L/p/day	1,4	88,6	860	L/day	**1204,0**	**76196**
COD	g/p/day	11,0	52	860	g/day	**9460,0**	**44720**
BOD	g/p/day	5,5	27	860	g/day	**4730,0**	**23220**
TSS	g/p/day	40,0	55	860	g/day	**34400,0**	**47300**
TN	g/p/day	9,0	1,2	860	g/day	**7740,0**	**1032**
NH4+ - N	g/p/day	9,0	0,1	860	g/day	**7740,0**	**86**
TP	g/p/day	0,8	0,4	860	g/day	**688,0**	**344**
K	g/p/day	2,8	0,8	860	g/day	**2408,0**	**688**

Source: *Own work based on Wielemaker et al. (2019) [60] plus Tervahauta, Taina's 'Phosphate and organic fertilizer recovery from black water' (2014) [63].*

* Total daily load of greywater 88,6 L/p/day does not consider 5 L/p/day of flushing activities

Assessing the dimension of the on-site recovery treatment plants - Urine

During the process of literature review in Chapter 4, it was possible to analyze two specific case-studies for urine treatment and nutrient extractions. These two systems were namely:

1. Struvite precipitation coupled with Ammonia stripping
2. Complete nitrification through an MBBR reactor and further distillation.

Concerning the first method, while struvite precipitation is a cheap and easy-to-install method to recover P from urine [64], it was studied that ammonia stripping could potentially work well only in in medium/large-scale districts with several hundreds of inhabitants [65]. With ammonia stripping almost all nitrogen can be recovered from source-separated urine, as well as nearly complete recovery of ammonia is possible. However, the need for strong bases and acids for the air stripping/acid adsorption method, together with the need of steam under high pressure and high temperature for steam stripping are challenges for small decentralized reactors [65]. On the other hand, the MBBR reactor used by the EWAG team at the VUNA project [64] proved to be easily scalable to treat urine up until 500 people. In this sense, both struvite precipitation and two MBBR reactor would work well in Cluster 2 of the Sluisbuurt neighborhood. However, due to the higher performances of nitrification process [64] and the possibility to extract all macro- and micro-nutrients at once, it was decided to assess the total urine treatment capacity of Cluster 2 using two MBBR reactors for nitrification. Furthermore, having two reactors is an advantage as if one need cleaning or repairing, still half of the urine flow is treated by the other reactor. Thus, having two reactors make the system more resilient to potential malfunction or maintenance operations.

Therefore, if the nitrification process is the one chosen to treat urine in the Cluster, the components of the system should be chosen and sized as follow (Tab 10):

- The two MBBR reactors are scaled based on the total ammonium load of the Cluster. As written in Table 9, the total daily load of $NH4^+$ is 7740 g/day. Estimating a nitrification rate of ammonium of min 400 - max 800 mg/L [64], it is possible to calculate the total volume of the two MBBR reactors (See calculation in Annex 2). After calculations, it resulted that the minimum volume for the reactors at the minimum nitrification rate is 19,4 m^3. Thus, to completely treat all nutrients from Cluster 2, two reactors of 9,7 m^3 are needed. Depending from the height of the nitrification room, it is possible to assess the spatial footprint of the two reactors. Considering that all ground floors in the Sluisbuurt neighborhood are at least 3,5 meters height [8], the column height of the reactor could be up to 3,0 m. Thus, if the reactors are positioned in the ground floor of one building, each would need a diameter of 2 m. To each reactor is associated a setting tank where the sludge coming from the nitrification process is collected and then either discharged or recirculated back into the nitrification reactors.

- Furthermore, the nitrification room would have to host the urine collection storage tank, an intermediate storage tank for treated stabilized urine and a final disinfected urine tank where urine is collected after UV pasteurization. Compared to the Vuna project in fact, it was decided to use UV pasteurization instead of the distillation process. UV disinfection is a type of water treatment that uses a low-pressure mercury arc lamp that emits UV light to kill pathogens in the water. This was decided after an interview with Bastian Etter, director of the Vuna project, and justified because the production spaces are already directly connected to the nitrification chamber, thus they won't need any further piping or transportation to bring the nutrient solution to the fertigation chambers. Furthermore UV disinfection does not require the same high temperature of the distiller to kill pathogens [64] and the requires less energy to operate.

- Concerning the urine collection storage tank, its dimension should be determined based on a retention time of at least 3 weeks (determined after the above cited interview with Bastian Etter). This is because the storage tank should be able to attenuate any daily, weekly or even seasonal fluctuations, as the nitrification process requires a steady input. Thus, considering 1204 L of urine per day, the storage tank should have a volume of (1204L x 21 days) 25,3 m3. The same logic applied to the MBBR reactor can be applied for the urine storage tank, dividing it into two tanks each of 12.7 m3 (h: 2,5m x d: 2,6m).

- Both the intermediate tank and the urine disinfected tank should be sized based on the daily urine load, and designed to attenuate possible daily fluctuations [64]. Considering a daily load of 1.2 L of urine and , the tanks were designed with a three day tolerance which resulted in a volume of 3,6 m^3 for each tank.

In conclusion, the components of the system are reported as follows (Tab. 13):

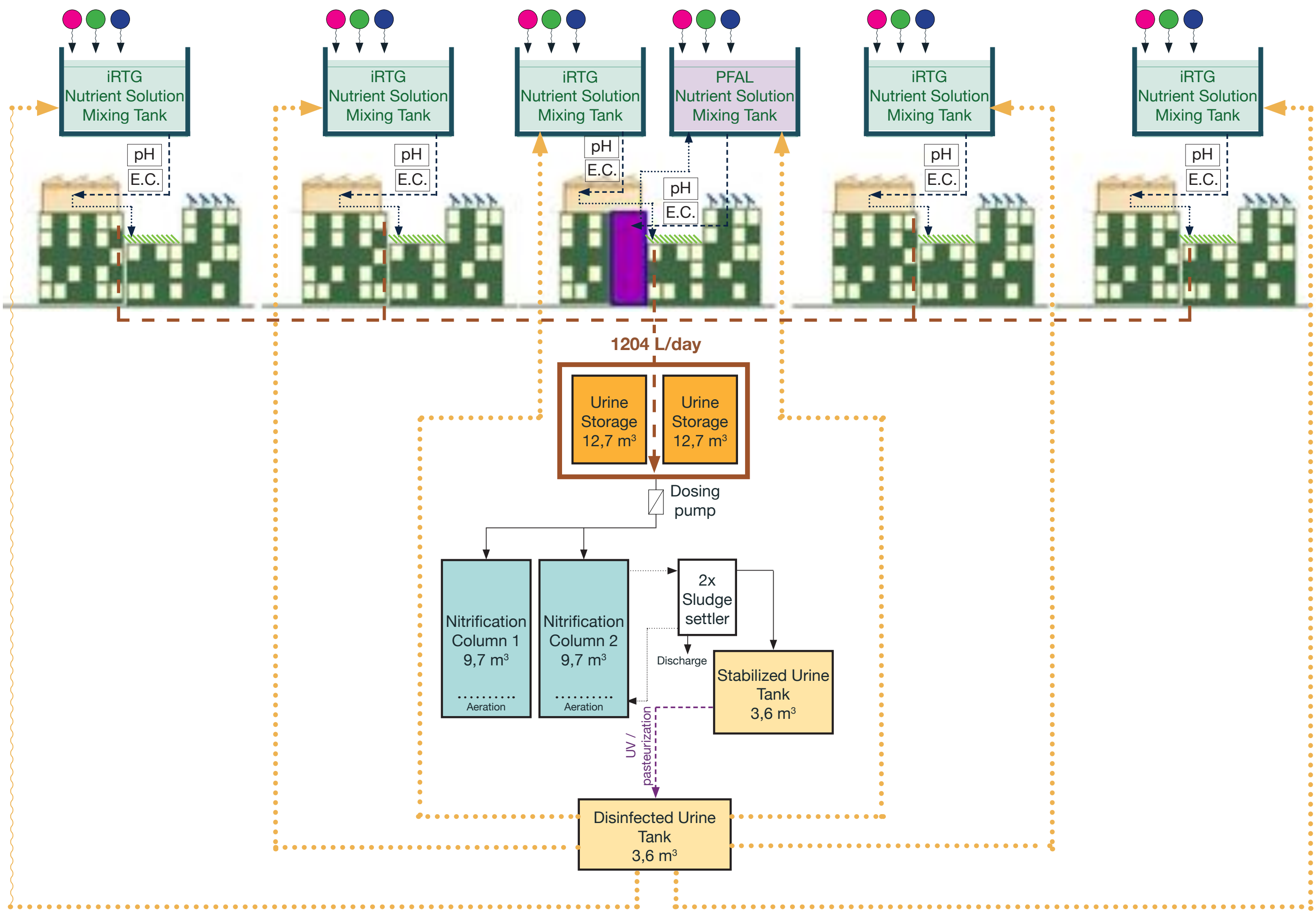
1. 2x urine collection tanks each with a diameter of 2,6 m.
2. 2x MBBR reactors with each with a diameter of 2,0 m.
3. 2x tanks, one for stabilized urine and the other for disinfected urine, each of 3,6 m^3 (h: 1,0m x A: 3,6 m^2).
4. 3x parallel units of UV pasteurization pipes each designed to carry 1,2 m^3 of treated urine.

Tab: 15: On-site urine treatment plant components

Components	Characteristics	Soil occupancy
Urine diverting toilets	Pipes: 50 mm diameter (d)	d: 50 mm
Total urine storage tanks volume	2 x 12,7 m^3 = 25,4 m^3	A_{tot}: 10,2 m^2
Nitrification column + Integrated sludge settler	MBBR reactors. 2 x 9,7 m^3 = 19,4 m^3	A_{tot}: 6,5 m^2
Stabilized urine tank	1204 L/day. Tolerance: 3 days. Tot. Volume = 3,6 m^3	A_{tot}: 3,6 m^2
UV disinfection	3x parallel pipe units each of 1.2 m3 (d: 0,5m x l: 6m)	A_{tot}: 9,0 m^2
Disinfected urine tank	1204 L/day. Tolerance: 3 days. Tot. Volume = 3,6 m^3	A_{tot}: 3,6 m^2
Connective and working spaces	Double of the installations area requirements [reported from the interview with Bastian Etter]	A_{tot}: 72 m^2
Nitrification technical room	Total expected dimensions of the technical room	**A_{tot}: 110 m^2**

As expected, the final dimensions of the decentralized urine treatment plant are relatively small compared to the size of the Cluster. The technical room can be then positioned ether in the basement (or ground-floor) in one of the building blocks that compose the cluster or in a specific designated area. Thus, all this considering, the final urine treatment concept is illustrated in Fig. 16.

Fig. 18: Nitrification treatment for urine in Cluster 2 - Flow concept



Source: *Own work*

In conclusion, the proposed method for nitrify urine takes into consideration the inputs provided by the scientists of the VUNA project [64] and adapt the technology to the project site. Based on the results of the power plant installed at the EWAG building in Switzerland [61], it is possible to expect a complete nutrient recovery from nitrification with 100% of P and K recovered, and > 99% of N recovered.

Assessing the dimension of the on-site recovery treatment plants - Greywater

During the analysis of natural based solutions (NBS) for greywater treatment in Chapter 4, it was done an in-depth analysis of two specific case studies concerning the application of green walls as natural solution for treating greywater. Indeed, green walls (together with green roofs) have recently emerged as feasible technology to treat wastewater in dense urban areas [66]. Vertical and horizontal surfaces are, in fact, ample, useful, and usable spaces in urban areas for the implementation of decentralized greywater treatment. In green walls, greywater percolate through planted pots filled with a combination of granular media such as vermiculite, sand, growstone, expanded clay, phytofoam, coco coir, and perlite [67]. The combination of media mix and the choice of the right plants activate the biological processes needed to remove pollutants from greywater. Due to their high aesthetic value and the limited surface they need to operate in dense urban areas, green walls present now a relevant advantage compared to other NBS system [68]. Both analyzed studies consistently removed pollutants from greywater and their implementation proved to be feasible in urban areas. The first analyzed case study proposed a green wall composed by climbing plants and a bottom saturated zone where the greywater was treated by the media and the climbing plants' roots. The second study proposed a classical configuration for a green wall where each plant was sitting in an individual pot attached to a supporting structure. For the purpose of this research, it was decided to use the system developed by Prodanovich et al. (2020) [69] that consisted in a potted design green wall. This choice was justified as pot design type is easier to manage compared to climbing walls, given the possibility to easily remove and substitute each pot in case of malfunctions of the systems. Furthermore, potted green walls don't need a saturated zone positioned at the ground floor to effectively treat the greywater, thus, they can completely be positioned on vertical surfaces reducing the system spatial footprint.

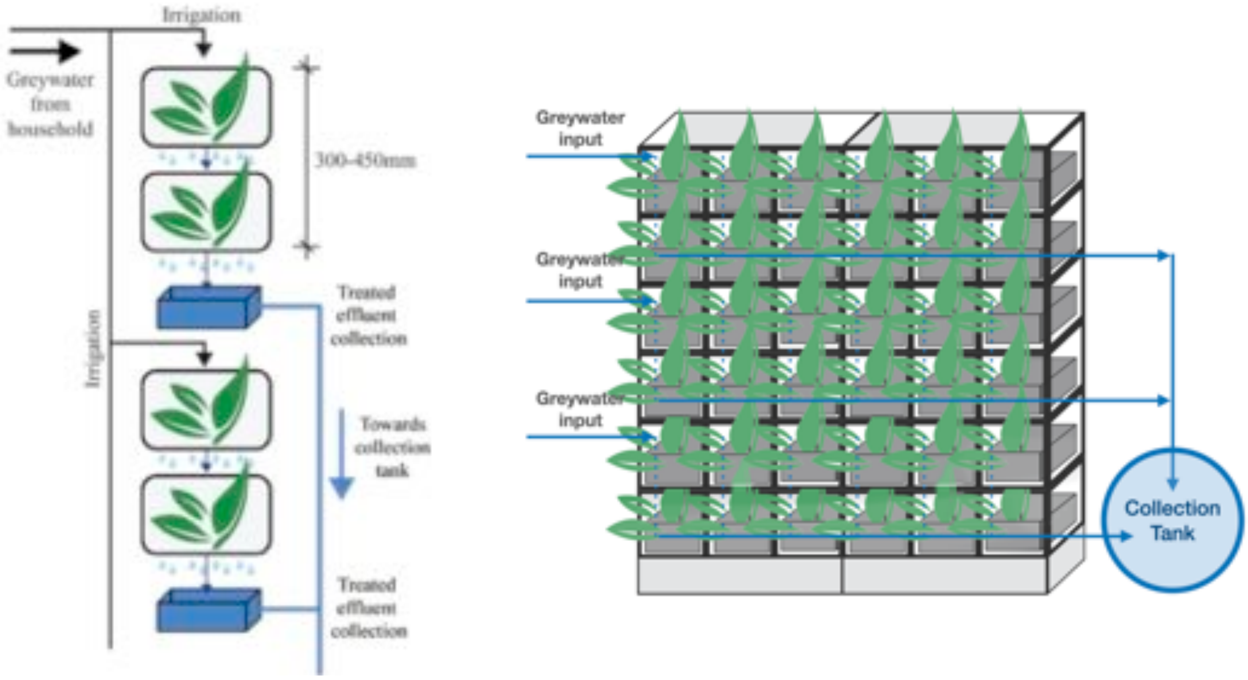
The potted green wall studied by Pogdanovic er al. [69] used the modular structure of the Gro Wall 4.5 designed by Atlantis and sold both in Australia and U.K. [70]. The structure of the green wall is made by recycled plastic box with an incision made on top of each box that could accommodate the irrigation pipes. Pots are wedged in the plastic structure and filled with 6 L of media mix to allow plants' growth (Fig. 17).

Fig. 19: Potted green wall structure

Credits: *Gro Wall 4.5 by Atlantis UK* - https://www.gro-wall.co.uk/gro-wall-4-5

As reported in Chapter 4, the results of this study indicates that a system with two pots, positioned one on top of the other, consistently removes pollutants from the greywater [69]. Due to the minimum dimensions of the system, to cover larger loads of greywater it must be replicated to reach the right size to treat the daily loading rate. Treated water can be collected from each two pots height system and redirected to a single collection tank (Fig. 0.).

Fig. 20: Characterization of the POT design Green Wall



Source: *Prodanovic, Veljko & Hatt, Belinda & Mccarthy, David & Deletic, Ana. (2020). Green wall height and design optimisation for effective greywater pollution treatment and reuse. Journal of Environmental Management. 261. 110173. 10.1016/j.jenvman.2020.110173 [67].*

As shown in Fig. 0. , the irrigation water is fed at the top of green wall and collected at the bottom. The total height of each treating double pot system is 450 mm and the total surface is 0,1125 m2 (0,45 x 0,25 m). Thanks to a recent article by Boano et al. [66], it is possible to estimate the Hydraulic Loading Rate (HLR) and the Organic Loading Rate (OLR) of the system proposed by Pogdanovic et al. [69]. Knowing the HLR and the OLR is fundamental to determine the size of the green walls in the Cluster. Considering the HLR of 382 L/m^2/day and a max of OLR of 128 g_{COD}/m^2/day [66], it is possible to calculate the minimum surface of the GW by dividing the total greywater daily load by the HLR and the total COD daily mass by the OLR:

Tab. 16: Assessing the size of the green wall

Daily load	Unit	Amount	Loading Rate	Unit	Size of the green wall m^2
Greywater	L/day	76196	382	L/m^2/day	199,5
COD	g/day	44720	128	g_{COD}/m^2/day	**349,4**

As it requires a bigger surface to treat the daily organic load compared to the Chemical Oxygen Demand, the OLR is the limiting factor by which assessing the final dimensions of the green wall. In this case, the final dimensions of the potted green wall is ca. 350 m^2. Considering that the pot design follows the indications reported in Chapter 4 and it is composed by two layers pot, each filled with 6L of media mix composed by 1:2 perlite and 1:2 coco coir, around 3.110 pots are required to effectively treat greywater. Thus, based on the literature review and the analysis of the case study [69] the green wall has the following characteristics:

Tab. 17: Characteristics of the green wall

Components	Characteristics	References
Chosen plant	*Carex appressa*	[69]
Substratum	1:2 Perlite; 1:2 Coco coir	[69]
Structure	Recycled plastic boxes	[70]
Dimension of the pots	0,04 m^2 (0,2 x 0,2 m)	[70]
HLR	382 $L/m^2/day$	[66]
OLR	128 $g_{COD}/m^2/day$	[66]
Total number of double layers pots	**3110**	Calculated
Green wall dimensions	**350**	Calculated

Considering a daily load of 76.196 L coming from all the dwellings in Cluster 2, and the reported performances of the two-layers potted green wall [69], it is possible to calculate the characteristics of the treated greywater and compared them to the requirements set by the European Union for its reuse in agriculture.

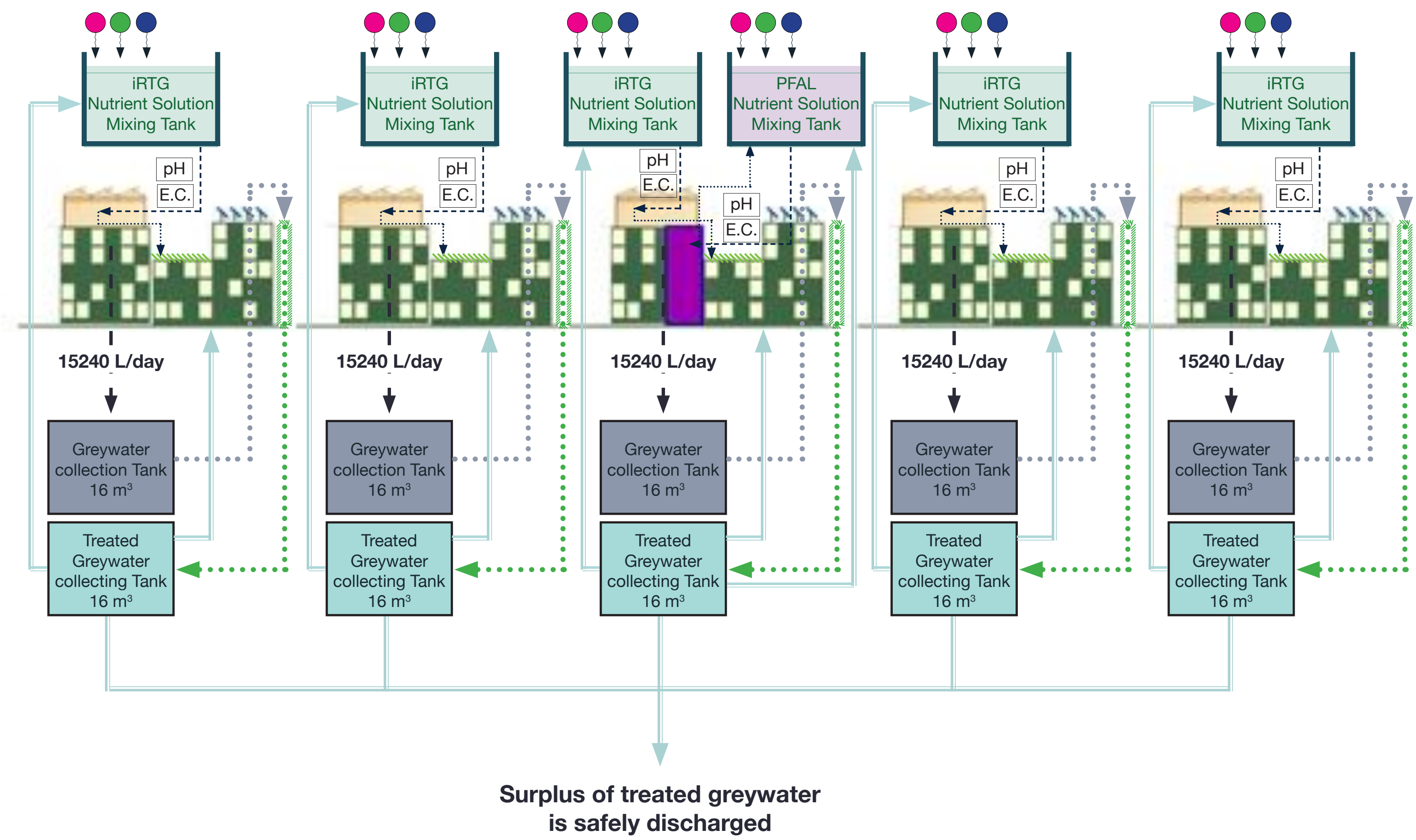
Tab. 18: Removal rates and final value of pollutant parameters in greywater

Pollutants	Influent concentration	Reference	Removal rate	Effluent concentration	Reclaimed water requirements [69]
COD (mg/L)	586,9	Calculated from [63]	94,4	**32,9**	**BOD ≤ 10 eq. COD ≤ 35 [67]**
TSS (mg/L)	620,8	Calculated from [63]	98,4	**9,9**	**≤ 10**
Turbidity (NTU)	167,9	[72]	97,6	**4**	**≤ 5**
TN (mg/L)	13,5	Calculated from [63]	91,8	**1,1**	**N.A.**
TP (mg/L)	4,5	Calculated from [63]	46,0	**2,4**	**N.A.**

As expected, the green wall consistently contribute to remove pollutants from greywater, complying with the new requirements established by the European Union [71]. However, further investigation should be conducted on E.coli content. The study from P. Et al [69] showed a 86% removal rate for E.coli, thus, further investigation on initial content of E.coli in the water should be done to assess the efficient removal of the bacteria, and the safe reuse in the production systems. Nonetheless, if there is a residue of harmful bacteria is still present in the treated greywater, it is possible to couple the green walls treatment with further pasteurization to ensure that no pathogens are given to the plants through the irrigation water.

Finally, considering the characteristics of the Cluster and the relative high dimension of the green wall, it is recommended that the total dimension of the green wall would be distributed across the 5 building blocks of the Cluster. This way, the total surface of the green wall can be divided by 5, resulting in five green wall each of 70 m^2. Assuming that the maximum height of the building blocks is given and it is 20 meters [8], a width of 3.5 meters only on each building block would be required to treat the approximately 15.240 L day^{-1} of greywater (76196 L day^{-1} / 5). Thus, based on this consideration, the final greywater treatment concept is reported in Fig. 2/ .

Fig. 21: Green wall greywater treatment for Cluster 2 - Flow concept



Source: *Own work*

In conclusion, as shown in Fig. 2/ , 15.240 L/day of greywater is collected from each building in a collection tank of approximately 16 m3 (slightly bigger than the daily load to absorb possible daily variations). From each tank, greywater is given to each green wall system of 70 m^2, where water is treated and collected in a collecting tank of 16 m3. However, the total water load reaching the collecting tank after percolating the green wall is expected to be less than the initial load due to evapotranspiration (ET). Thus, considering an average annual ET of 525 mm/year [73], equivalent to approximately 1,44 L/m^2/day, it is possible to estimate the water loss in 101 L/day for each building, accounting for 0,6% of the initial load. The reclaimed water reaching the collecting tank fits within the requirements provided by the European Union (as shown in Tab. 8) and thus it can be safely used for both agricultural irrigation and other non-potable uses like washing and flushing. The excess water, calculated in the latest section of this chapter, can be safely discharged or even stored for irrigating other agricultural fields.

3.5 Step 4: Verify the feasibility of the system

Finally, the objective of this last step is to verify how much water and nutrients can be recovered by the system described in the first three steps. It was already demonstrated the the food production system constitute an actual economical gain when comparing the equivalent energy costs of the produce with their retail price. Here, the feasibility of the system will be assessed considering all the other operational costs such as water-cost, fertilizer-cost, and labor-cost excluding the initial investment costs required for installation. Furthermore, it will be assessed how much water and fertilizer can be saved thanks to the greywater and urine treatment described above. The feasibility of the system will be studied in three phases:

- *Phase 1 - Assessing macronutrients concentration in urine-based fertilizer:* Compare the concentration of recovered nutrients with the fertilizer requirements of the crops.
- *Phase 2 - Assessing greywater flows:* Compare the total amount of recovered water with the water requirements of the crops. Determine how much water can be recycled back in the building and the amount of water that will be discharged.
- *Phase 3 - Assessing costs:* Assess the costs related to the operational management of the food production systems and compare them to the relative water and fertilizer costs savings derived by the wastewater treatment.

Phase 1 - Assessing macronutrients concentration in urine-based fertilizer

In a previous section of this Chapter it was defined what was considered the best food production scenario for highly dense urban district such the Cluster 2 in the Sluisbuurt. The energetic calculations, in fact, demonstrated that producing fruit crops like berries in dense urban environments may not be sustainable. In this sense, the food production strategy focused only on Fruit Vegetables and Leafy Greens as macro-category of crops. The nutrient and water requirements of these crops are listed in Table 14 and were taken or extrapolated from the literature and recent experiments conducted at the University of Bologna. Specifically, the indicated nutrients requirements refer to Tomatoes [52], for what concerns the Fruit Vegetables crop, and *Lectuce Sativa* [53], for what concerns the Leafy Greens crop. Thus, when producing different plants that belong to the same macro-category of crops, few differences in the nutrients requirements might be expected.

As the fertilizer composition required for the crops found in literature was expressed in milimol, it was necessary to operate a conversion in mg/L to compare the required concentrations with the one found in the treated urine. As both nitrate ($N\text{-}NO_3^-$) and phosphate (H_2PO_4) were expressed in the form of N and P, to find their concentration in mg/L it was only needed to multiply the mM times the molecular weight of N and P. Same thing was done to convert K concentrations. Once the concentrations have been determined, it is possible to compare the required concentrations with the concentration of nutrients in treated urine.

Tab. 19: Nutrients and water requirements of the selected crops

Chemicals	Unit	Leafy greens	Fruit vegetables
Nutrients requirements	mM	$N-NO_3^-$ = 12,4 [53] P = 1,1 [53] K: 7,2 [53]	$N-NO_3^-$ = 21,1 [52] P - H_2PO_4 = 1,56 [52] K = 10,8 [52]
N	mg/L	173,6	295,4
P	mg/L	34,1	48,4
K	mg/L	281	421
Cultivated production area	m2	946	3520
Daily water requirements	L/m2/day	2,5	1,55
Tot water requirements	L/day	2365	5456
Percentage of water required	%	30	70

Based on the calculation in Tab. 14, it emerges that 70% of the nutrient-rich water reclaimed from urine will go to the 5 greenhouses, and 30% to the leafy green PFAL. In this scenario, the concentration of urine macronutrients in the mixing tanks is expected to be:

Tab. 20: Urine macronutrients concentration in the nutrient solution divided by crops

Parameters	Unit	Leafy greens	Fruit vegetables
Daily load of urine water	L/day	361	843
Total mass of N contained in urine	g/day	2320,7	5419,3
Total mass of P contained in urine	g/day	206,3	481,7
Total mass of K contained in urine	g/day	722,0	1686,0
Total water requirements	**L/day**	**2365**	**5456**
Daily load of added greywater	L/day	2004	4613
Total mass of N contained in geywater	mg/L	27,1	62,5
Total mass of P contained I greywater	mg/L	9,0	20,8
Total mass of K contained in greywater	mg/L	18,1	41,7
Finale N concentration in the nutrient solution	**mg/L**	**992,8**	**1004,7**
Finale P concentration in the nutrient solution	**mg/L**	**91,0**	**92,1**
Finale K concentration in the nutrient solution	**mg/L**	**312,9**	**316,7**

The final urine-based fertilizer concentration found in table 15 was obtained by dividing the total mass of N, P, and K both in urine and greywater by the total water requirements of the each crop. To calculate the mass of N, P, and K, the operation that was done was to dividing the total daily mass of each element (shown in Tab / 2) by the daily load of urine (1204L) and then multiply the results by the daily load of urine water assigned to each crop. For instance, to calculate the final concentration of N, the used equation was:

$$Nc = \frac{Nu(mass) + Ngw(mass)}{Wreq} \cdot 1000$$

- Where Nc is the Nutrient concentration
- N_u and N_{gw} (mass) are the the masses of urine and greywater expressed in g/day contained in the nutrient solution
- W_{req} is the water requirements of each specific crop
- The total result is multiplied by 1000 to convert g/L into mg/L.

The total mass of N for urine and greywater was calculated as follow::

$$Nu(mass) = \frac{TN(u) \cdot DL(u)}{V(u)} \qquad Ngw(mass) = \frac{TN(gw) \cdot DL(gw)}{V(gw)}$$

- Where TN_u and TN_{gw} represent the TN mass found in urine and greywater as reported in Table 9.
- DL is the daily load of urine and added greywater in each of the two systems
- V is the total daily volume of greywater reported in Table / 2 .

Thus, once that all requirements are calculated and that the final concentration of N, P, and K in the urine-based fertilizers has been determined, it is possible to compare the commercial fertilizer composition with the urine-based fertilizer:

Tab. 21: Comparison of commercial and urine-based fertilizer in Cluster 2

Crops	Macronutrients	Unit	Fertilizer recipe	Urine-based fertilizer
Leafy greens	N	mg/L	173,6	992,8
	P	mg/L	34,1	91,0
	K	mg/L	281	312,9
	P:N ratio	NA	0,20	0,09
	K:N ratio	NA	1,62	0,32
Fruit Vegetables	N	mg/L	295,4	1004,7
	P	mg/L	48,4	92,1
	K	mg/L	421	316,7
	P:N ratio	NA	0,16	0,09
	K:N ratio	NA	1,43	0,32

As shown in Table 16, the N and P concentrations in urine are much higher than in the fertilizer recipes found in literature [52, 53] while K is slightly higher in the leafy greens and slightly lower in the Fruit Vegetables. As expected, the ratio between P and N and K and N in urine-based fertilizers was found to be relatively lower compared to synthetic fertilizers. Nonetheless, it was reported in Chapter 4 that the ionic form of both phosphorus and potassium makes it readily available for plant absorption upon application [75]. In order to lower the the concentrations of N, P, K in the urine-based fertilizer there are two possible strategies:

1. Use only the amount of urine needed to match the commercial fertilizer recipes. The advantage of this strategy is that the there is no need to increase the amount of treated greywater in the nutrient solution mixing tanks. Therefore, the dimensions of the tank can be safely measured to comply with the given water requirements. However, in this scenario the excessive urine will be discharged without going through the hydroponic treatment. Nonetheless, the high amount of treated greywater that is discharged may allow to dilute the excessive content on nutrients in the excessive discharged urine so that the concentration of pollutants in the discharged water consistently comply with discharge water standards.

2. Dilute the urine-based fertilizer with an increasing amount of treated greywater. The advantage of this strategy is that all urine is recovered and used. However, increasing the amount of treated greywater in the mixing tank would increase the size of the tank and its relative weight. Thus, if the mixing tanks are positioned on the roof, next to greenhouses, increasing the quantity of water may result in structural problems.

Based on these considerations it was decided to opt for Strategy 1, renouncing to some of the treated urine in order to achieve better yields conditions. Thus, looking at Table 16, it has been decided to use P as limiting factor. This is because P is the most pollutant mineral of the fertilizer composition [63] and therefore the most important one to recover. In this scenario, if P concentration are set based on the original fertilizer recipe [52, 53], it is possible to calculate the final diluted composition of the urine based fertilizer.

Table 00a and 00b report the final amount of urine and greywater used in the production systems and the new urine-based fertilizer concentration compared to the commercial fertilizer recipe. Due to the complexity of the calculation and the multiple variables of the equation, the new concentrations were calculated using Newton iterative method in the Excell file [74] (See Annex 3 for the complete calculations).

Tab. 22a: Total use of urine and greywater to match the required P concentration

Paramters	**Units**	**Leafy greens**	**Fruit Vegeatbles**
Volume urine	L/day	126	429
Volume of added grey water	L/day	2239	5027
Total water required	**L/day**	**2365**	**5456**
N concentration	mg/l	354	516
P concentration	mg/l	34	48
K concentration	mg/l	114	165
Total volume of urine used	**L/day**	**555**	
Total volume of greywater used	**L/day**	**7266**	

Tab. 22b: Final comparison of commercial and diluted urine-based fertilizer used in Cluster 2

Crops	Macronutrients	Unit	Fertilizer recipe	Urine-based fertilizer
Leafy greens	N	mg/L	**173,6**	**354,0**
	P	mg/L	**34,1**	**34,0**
	K	mg/L	**281**	**114,0**
	P:N ratio	NA	0,20	0,10
	K:N ratio	NA	1,62	0,32
Fruit Vegetables	N	mg/L	**295,4**	**516,0**
	P	mg/L	**48,4**	**48,0**
	K	mg/L	**421**	**165,0**
	P:N ratio	NA	0,16	0,09
	K:N ratio	NA	1,43	0,32

In this scenario, the TN in excess will cause lower yields as happened in the experiment reported in Chapter 4 by Shirly Tentile M. et al. (2020) [75] and already reported in the previous section in Table 5. y Furthermore, in closed systems the excess of N may deposit in the mixing tanks, increasing the salinity of the nutrient solution after multiple cycles. For this reason, as the whole BIA system works as a closed system where the water is recirculated directly from the building blocks, it is recommended to purge the surplus of nutrient solution and redirect it to the green roofs. This way, the surplus water containing the remaining nutrients can be used for irrigating the green roofs adjacent to the greenhouse foreseen by the Sluisbuurt plan [8]. On the other hand, K concentrations are now lower compared to the commercial fertilizer composition. Thus, the nutrient solution should be corrected with regards to K, adding a concentration of 167 mg/L for leafy greens and 256 mg/L for Fruit Vegetables. In this sense, 395 g/day of K must be added to the nutrient solution for the leafy greens, and 1.397 g/day of K must be added to the Fruit Vegetables.

In this scenario, another solution would be to to further dilute the urine based fertilizer to reach the optimal N concentrations. In doing so, only 300 L/day of urine would be used (25% of the initial load), and P and K concentrations would drop dramatically (For leafy greens P: 18 mg/L; K: 59 mg/L. For fruit vegetables P: 29 mg/L; K: 96 mg/L). In conclusion, diluting urine-based fertilizer to match P or N concentration requirements are both valid solutions that allow to recover most nutrients from urine. For the purpose of this research, the urine and water flows in the Sluisbuurt was calculated for urine-based fertilizer diluted to match P concentration requirements.

Concerning the use of treated wastewater, the total urine that will be used as fertilizer is now 555 L/day, approximately 46% of the initial load. In this context, 54% of the treated urine in the MBBR reactor won't be used as fertilizer. Therefore, further research should be done to implement the usage for the treated urine (i.e. fertilizer for soil-based agriculture) or, to revise the modeling of the MBBR reactor to treat only the urine that is needed by the food production systems. However, if the treated urine is not used as fertilizer, it could be safely discharged considering that the MBBR reactor has an average of 95% COD removal from urine [76]. In this specific case, the total mass of COD in the remaining water is 5100 g/day (concentration of COD multiplied by the discharged amount of water). Thus, after treatment, the concentration of COD in the effluent water would be 393 mg/L, way higher than the 125 mg/L required by the EU standards [77]. However, treated urine effluent will be mixed with the effluents coming from the greywater treatment which has a very low concentration of COD as demonstrated in Table 13. Thus the total COD concentration in the discharged water is calculated in the next section (Phase 2).

Phase 2 - Assessing greywater flows

As determined in the previous section of this Chapter, a total green wall surface of 350 m2 is needed to treat the whole daily load of grey water coming from the five building blocks of the Sluisbuurt. Thus, to reduce the total surface of the greywater treatment it was decided to separate the green wall surface in five, assigning a green wall of 70 m2 to each building block. Furthermore, in doing so, it becomes easier to collect greywater as it is always recirculated within each building block. In this context, each 70 m^2 green wall can treat 15.240 L of urine per day. Finally, considering an average ET=1,44 L/m^2/day [73], a total water loss of 101 L/day per building is to be expected. In this regard, the total daily load of usable reclaimed wastewater is 15139 L/day. Based on this data, the greywater flow in each building block is described in Table 01.

Table 01a shows the configuration in one of the building blocks of the Cluster, focusing on that particular block that hosts both 1x Greenhouse of 704 m^2, and the leafy greens PFAL.

Tab. 23a: Reclaimed greywater flow in one building block hosting both 1x iRTG and the PFAL

Parameters	Unit	Amount
Total daily load from urine diverting toilets in each building block	L/day	15240
Water loss due to ET	L/day	101
Total reclaimed water	L/day	15139
Water requirements of 1x Greenhouse of 704 m^2	L/day	1091,2
Daily load of urine water for 1x Greenhouse	L/day	85,8
Water requirements of 1x PFAL of 946 m^2 of total cultivated production area	L/day	2365
Daily load of urine water for 1x PFAL	L/day	126
Total daily water requirements	**L/day**	**3456,2**
Total added greywater	**L/day**	**3244,4**
Reclaimed water surplus	**L/day**	**11894,6**

Tab. 23b: Total water flow in Cluster 2 and in the five building blocks

Parameters	Unit	Amount
Total greywater used for 5x iRTGs	L/day	5027
Total greywater used for PFAL	L/day	2239
Total greywater used	**L/day**	**7266**
Total greywater used for 1x iRTG	L/day	1005,4
Total greywater used for 1x iRTG and 1 PFAL	L/day	3244,4

Thus, as demonstrated in Tab. 01, it is required a daily load of 3244,4 L/day for the irrigation of 1x greenhouse and 1xPFAL in the building block that hosts both systems. In the other four building blocks, each hosting 1x greenhouse, the total water needed for irrigation is 1005,4 L/day. Thus, in the the whole Cluster, the volume of treated greywater reused for irrigation is 7266 L/day over the total daily load of 76196 L/day, approximately 10%. Therefore, the remaining treated greywater (68930 L/day) can be reused in the building blocks for non-potable uses such as washing and flushing.

Considering the average Dutch composition of greywater reported by L. Hernandez Leal [78], it is possible to calculate the exact amount of water that can be reintroduced back into each building block.

Tab. 24: Average Dutch greywater composition

Source	Unit	Volume
Shower and bathing	L/person/day	52,3
Hand basin	L/person/day	5,3
Laundry	L/person/day	17,2
Kitchen	L/person/day	13,8
Flushing with gravity urine diverting toilets [63]	L/person/day	5
Total load + flushing	L/person/day	93,6

Thus, assuming that each building block has the same number of inhabitants (172) and considering the average Dutch domestic wastewater composition reported in Table 02, it is possible to recirculate in each building 860 L/day for flushing and 2.958,4 L/day for laundry, equivalent to a total of **3.818,4 L/day** in each building block. Thus, a total of 19092 L/day of treated greywater can be recovered and used in the apartment building blocks for washing and flushing. Finally he total amount of daily recovered water in the whole cluster is **26358 L/day**, 35% of the total daily load. The remaining treated greywater (49838 L/day) can be safely discharged or stored for other utilizations, such as watering the parks surrounding the neighborhood. In case of discharge, it is important to calculate the final concentration of COD considering that the treated greywater effluent would mix with the treated urine effluent that has a COD concentration of 393 mg/L. Hence, the final concentration of COD in discharged treated wastewater is reported in Table 20.

Tab. 25: Calculation for the final concentration of COD in discharged treated wastewater

Loads	Unit	Amount
Discharged urine	L/day	649
Discharged greywater	L/day	49838
COD concentration in treated urine	mg/L	393
COD concentration in treated greywater	mg/L	32,9
Total mass of COD in discharged water	mg/day	1895,0
Total volume of discharged water	L/day	50487
Final COD concentration	**mg/L**	**37,5**

In conclusion, a total volume of **50487 L/day** of treated wastewater can be discharged safely as the final COD concentration is consistently within the limit of 125 mg/L required by the EU standards [77].

Phase 3 - Assessing operational costs

The third and final phase aims to assess the economical feasibility of the food system. The objective of the BIA model is to provide enough safe food to the local community. As stated at the beginning of this Chapter, the objective of this project is to experiment with a building-integrated agriculture model, assessing its production capacity with regards to circular strategies connected to wastewater treatment and recovery. In this sense, the produced food is not intended for commercial purposes, but as a good practice that could show how to implement the sustainability of urban food systems and implement local healthy diets. Therefore, the production systems do not have commercial purposes. In this scenario, all the costs concerning the production will hypothetically be paid by the dwellers. The costs considered in this research refer exclusively to operational costs, not considering the installation costs, which will require further research, especially concerning the installation of the urine treatment process. Thus, as all the produced food is given to the inhabitants of the neighborhood, the idea is to calculate the operational costs and compare them to the retail price of the produced food. The analyzed costs are then: i) Energy costs, which were already discussed in section 3.3; water costs (Tab. 24a); labor costs (Tab. 24b), based on the literature review [50, 80].

Tab. 26a: Equivalent water cost per kg of produce

Production system	Parameters	Units	Rerence	Amount
PFAL - Leafy greens	Water costs	€/m³	[55]	0,79
	Total water requirements	m³/day	[Calculated from 51]	2,365
	Total water costs PFAL	€/day	[Calculated from 51]	1,9
	Total production PFAL	kg/day	[Calculated]	189,0
	Eq. water prize per kg of leafy greens	€/kg	[Calculated from 51]	**0,010**
Rooftop greenhouses - Fruit vegetables	Water costs	€/m³	[Calculated from 50]	0,79
	Total water requirements	m³/day	[Calculated from 50]	5,456
	Total water costs iRTGs	€/day	[Calculated from 50]	4,3
	Total production iRTGs	kg/day	[Calculated]	387
	Eq. water prize per kg of Fruit Vegetables	€/kg	[Calculated from 50]	**0,011**

Water costs were calculated considering both the PFAL and the rooftop greenhouses as open systems. This is because both systems can count on a daily provision of treated greywater, and thus, don't need to further recirculate nutrient solution to optimize water consumption. Furthermore, the presence of many parks, green roofs, and green areas allow the reuse of the effluent water from the hydroponic systems for irrigation in other areas of the neighborhood. Therefore, related costs of water are higher than what could be expected from high-tech Dutch greenhouses and plant factories. However, as the whole amount of water is provided by the treated greywater coming from the building blocks, water-related costs can safely be assumed as zero. In this sense, Tab. 21a provides interesting information regarding water consumption in hydroponic systems. Indeed, if water is not recirculated, either from the buildings like in the case of the Sluisbuurt or from a closed system, water consumption would be unsustainable. Thus, using treated greywater or rainwater is highly recommended, also in closed-loop systems.

Tab. 26b: Total labor costs per year and equivalent labor costs per kg of produce

Production system	Parameters	Unit	Amount	References
PFAL - Leafy greens	Labour costs	€/year	**53200**	[79]*
	Total production	kg/year	68985	[Calculated]
	Equivalent labor cost per kg of produce	€/kg	**0,8**	[Calculated]
Rooftop greenhouses - Fruit vegetables	Cultivation labor	hours/1000m² year⁻¹	950	[50]
	Total surface**	m²	13000	[Calculated]
	Total labor hours	hours/year	12350	[Calculated]
	Average hourly wage	€/hour	22,70	[80]
	Total labor costs	€/year	**280345**	[Calculated]
	Total production	kg/year	130305	[Calculated]
	Equivalent labor cost per kg of produce	€/kg	**2,2**	[Calculated]
Total costs	Total labor cost	€/year	**333545,0**	[Calculated]

*Labor costs reported by Avgoustaki et al. [79] were calculated in a PFAL in Copenhagen of similar configuration and dimensions of the PFAL consider here for Cluster 2. However, the average working wage was considered higher compared to 22,70 €/hour [80] reported for the greenhouse. In this sense, PFAL labor costs could be even lower in Amsterdam compared to Copenhagen.
** The total iRTGs surface considered for the labor costs calculation is different from the actual iRTGs surface (3520m2). This is because when calculating labor costs it was considered the whole rooftop surface indicated by the plan. This choice is justified by the fact that the reported labor costs 950 hours/1000m^2 $year^{-1}$ [50] are considered for high intensive advanced Dutch greenhouses. In urban areas, spaces are not optimized like in these greenhouses, in fact, the 5x iRTGs are scattered on top of five different roofs of five different building blocks. Thus, more personnel is expected to be hired compared to commercial Dutch greenhouses.

Looking at Tab 24b, it is possible to see how labor costs have a great impact on the whole operational costs of the production systems. However, as reported in the caption above, costs are estimated based on the literature review and personal considerations. In this sense, even if they seem plausible, real operation costs may be lower. This is because on one hand, labor costs of PFAL were referenced to a location (Copenhagen) that has higher hourly wages, and, on the other hand, the costs for the iRTGs were considered in a worse-case-scenario where the total rooftop surface was considered for production.

Concerning fertilizer costs, it was harder to determine the actual economic gain compared to commercial fertilizer, as this research focused mostly on N, P, and K while fertilizer recipes have different ionic forms of these nutrients plus the addition of other micronutrients that were not considered here. For instance, further research should address the content of Ca in urine-based fertilizer as it proved to be a limiting factor in the experiment in South Africa [75] reported in

Chapter 4. However, as described by the scientists of the VUNA project, the nitrification process in the MBBR reactor allows the complete recovery of micronutrients [64]. In this sense, further research on the concentration of micronutrients in urine-based fertilizer should be done when using treated urine for hydroponic plants. Furthermore, the urine-based fertilizer produced with urine treatment in Cluster 2 showed a lack in K when further diluted to match P requirements. In this sense, additional costs concerning the integration of K can be expected. However, considering that fertilizer costs are a low percentage of the total operational costs of the hydroponic systems [50] and that all P and N are recovered during urine nitrification, it was decided to consider the costs of added K irrelevant.

In conclusion, as most macronutrients and all the water needed for production are recovered from the Cluster's wastewater, they won't affect the operational costs of the food production systems in the Sluisbuurt. However, both labor and energy costs have a significant impact on production. Moreover, further research should be conducted on the installation costs, such as the MBBR reactors and the green walls. Other costs like planting materials, structural materials and construction, pipings, tanks, and nutrient solution correctors should be also taken into consideration to assess the real costs of the urban food production systems. Nonetheless, the findings of this thesis demonstrated that water, energy, labor, and, fertilizer costs can be amortized by an actual saving on the supermarket bill thanks to the interactions between buildings and the production system. Indeed, as shown in Table 25, the equivalent price per kilogram of produce for leafy greens is just 66% of the retail price, while for fruit vegetables are slightly higher (0,08 €). However, labor costs in the rooftop greenhouse may be lower as the estimation that was made in this Chapter considered the whole rooftop surface as productive, instead of considering just the specific dimension of the five greenhouses.

Tab. 27: Total energy, water, and labor costs compared with produce retail price

Parameters	**Unit**	**PFAL**	**Rooftop greenhouses**
Equivalent energy costs per kg of produce	€/kg	1,7	0,5
Equivalent water costs per kg of produce	€/kg	0	0
Equivalent labor costs per kg of produce	€/kg	0,8	2,2
Equivalent fertilizer costs per kg of produce	€/kg	0	0
Retail price per kg of produce	€/kg	3,7	2,6
Total savings on the supermarket bill	**€/kg**	**1,2**	**-0,08**
Daily expected consumption per capita	g/person/day	220	180
Monthly expected consumption per capita	kg/person/month	6,6	5,4
Monthly savings per capita on the supermarket bill	**€/person/month**	**7,8**	

In conclusion, considering that an hypothetical family of four would consume 26,4 kg per month of leafy greens and 21,6 kg of fruit vegetables, their potential savings on the supermarket bill would be 31,2 €/month, the equivalent of **374,4 €/year**. Based on this, it would possible to calculate the total yearly savings on the supermarket bill from the inhabitants of Cluster 2, and compared them to the required installation costs for the PFAL and the iRTGs that were not reported here. Once the installation costs are known, it would be then possible to determine how many years would take to the Sluisbuurt families to return on the investment costs of the entire food production systems.

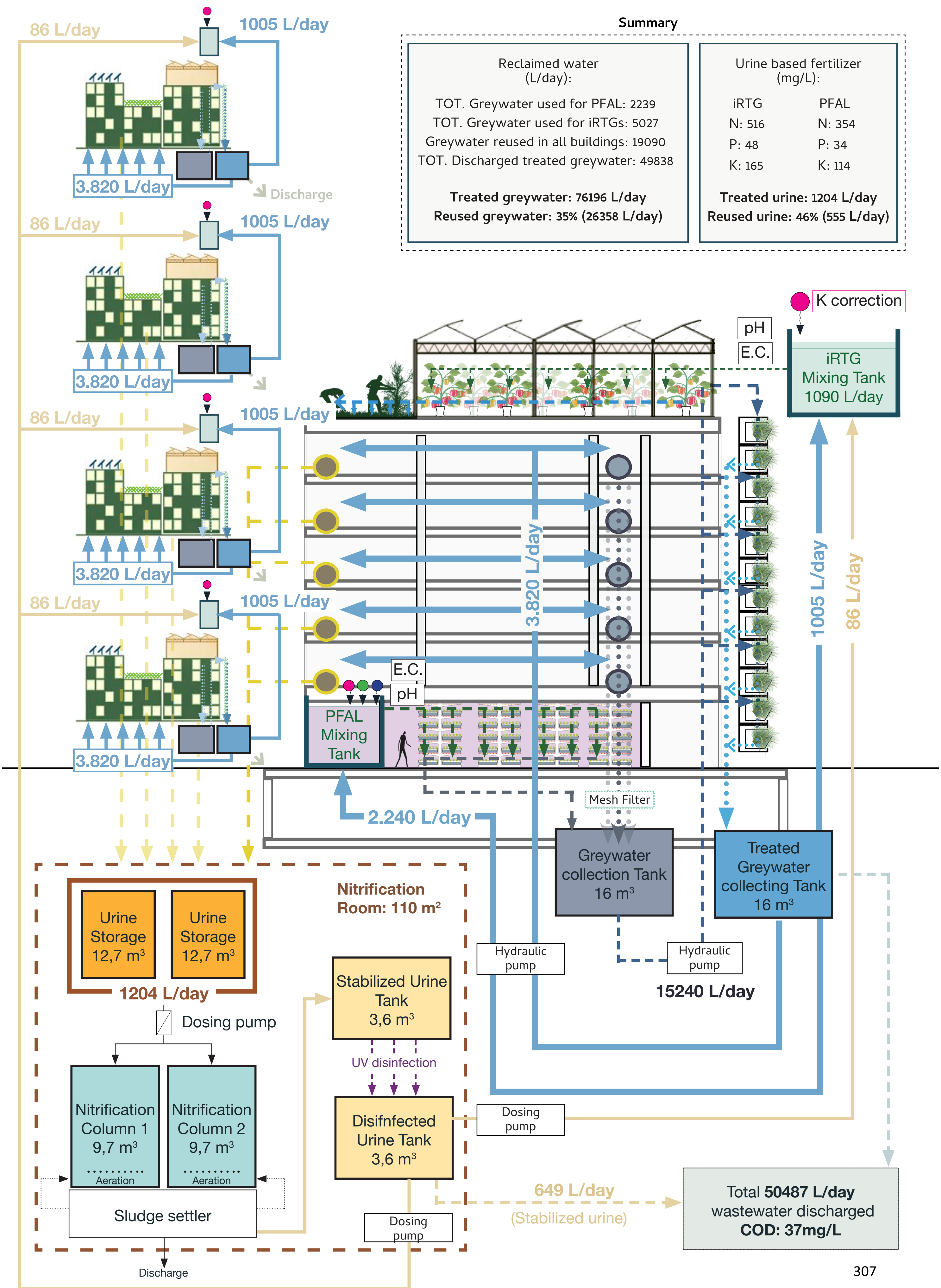
3.6 Final discussion

The BIA model proposed for Cluster 2 of the Sluisbuurt is the result of a progressive set of choices that were aided by the use of the proposed methodology. The initial configuration, consisting in a PFAL for berries and leafy greens, and a Venlo-type rooftop greenhouse for fruit vegetables, was redacted after the analysis of the total energy required to produce berries. Thus, it emerged the importance of selecting crops based on their production capacity, reducing the spatial footprint of the production methods and, therefore, their energy requirements. In this regard, the final proposed model consisted in the cultivation of only two macro-categories of crop: i) leafy greens, and ii) fruit vegetables. The daily expected consumption of each crop was determined based on Dutch FBDGs [40] and the governmental report on Dutch diets [54]. Based on the expected consumption data, and the reported yields of the crops, it was possible to model the complete food production system in Cluster 2 to satisfy the expected local food demand. The proposed system could produce roughly 160% of the total food demand of vegetables in a high density neighborhood. On a broader scale, considering that Amsterdam will build 52.500 homes within the city boundaries by 2025 [7], it would be possible to produce enough vegetable food for this whole new Amsterdam population by implementing BIA projects on 32.800 new homes. Assuming a similar urban density of the Sluisbuurt - 150-200 households per hectare - a total of 164-220 ha of would be needed to feed the new 'Amsterdammers'. In this regard, the specific food production system developed for the Sluisbuurt consists in:

- 5x integrated rooftop greenhouses. Each rooftop greenhouse is located on the roof of one building block in Cluster 2 and has a total floor area of 704 m^2.
- 1x PFAL with a cultivated surface of 946 m^2, the equivalent floor space area of 189 m^2 when considering that plants are cultivated on 5-levels trays. Furthermore, the final total area of the PFAL was determined based on a similar PFAL recently installed at the University of Bologna, resulting in a total spatial footprint of 245 m^2 including the connective spaces and the installation room.

Once defined the food production model, it was possible to calculate the amount of treated urine and greywater flowing from the building blocks into the hydroponic systems. Interestingly, Nitrogen and Phosphorus were in higher concentration compared to the fertilizer recipes found in the literature [51][52]. Therefore, the treated urine had to be further diluted with greywater to match P requirements. The dilution was carried on by discharging 56% of the treated urine, to avoid increasing the volume in the mixing tanks. That would dramatically increase the tanks weight, compromising the stability of the roof structure. In this sense, further research is needed to assess other scopes for the unused treated urine. However, when diluted with the effluent of treated greywater, urine could be safely discharged. COD concentration was, in fact, way below the recommended EU standards [77]. Another interesting development of the research would be to size the MBBR reactor to treat just the needed amount of urine. This would result in lower investment costs and lower energy consumption. The following step was to assess the total flow of treated greywater needed to comply with crops' water requirements. As expected, pollutants concentration in treated greywater was consistently below the new standards proposed by the EU for treated greywater reuse in agriculture [71]. The greywater was treated on each building through a vertical green wall of 70 m^2. The greywater coming from the dwellings was collected for each building in a collecting tank and then pumped into the green wall from the top. Treated greywater was then collected in a tank of 16 m^3 located at the bottom of the green wall. From there, an average of 10% of the treated greywater is used for irrigation and another 25% is recirculated within the building blocks for flushing and washing. The rest of the treated greywater was safely discharged without any health hazards connected to the presence of pollutants in the discharged water. Further research can be done to find a better use of the excess treated greywater. For instance, in new neighborhoods like the Sluisbuurt, it could be used for the irrigation of parks and garden located in the area. To better visualize the wastewater treatment system in Cluster 2, Figure 22 shows the water mass flow within the five building blocks and the production system, with particular focus on that one building that hosts both the rooftop greenhouse and the PFAL.

Fig. 22: Water masses flow in Cluster 2



Looking at Figure 22, it is possible to make a summary table of the whole components of the the BIA cluster needed for wastewater treatment:

Tab. 28: Components needed for the wastewater treatment in the Sluisbuurt

Urine		**Greywater**	
Treatment		**Treatment**	
Components	Characteristics	Components	Characteristics
Urine diverting dry toilets	Allow to collect urine without contamination	5x collecting water tanks	Collect greywater from each building block
2x Urine storage tanks	Store urine with a retention time of 3 weeks.	5x mesh filters	Help separate the suspended solids that may clog the system
2x Dosing pumps	Pump the right amount of urine inside the nitrification reactors	5x Geen walls	70 m2 each
2x MBBR reactors with integrated sludge settlers	Thanks to the integrated biomass carriers are able to recover all nutrients from urine		6.5 L media mix of 1:2 coco coir and 1:2 perlite
1x Stabilized urine tank	Collects the urine after nitrification		Planted with *Carex appressa*
3x UV disinfection parallel units	Transparent pipes integrated with UV lights for disinfection		Total double layers pots: 622 per green wall
1x Disinfected urine tank	Collects the disinfected urine	5x collecting treated greywater tanks	Collect the treated greywater at the bottom of each green wall
1x Dosing hydraulic pump	Pump the disinfected urine rich in nutrient in the nutrient solution mixing tanks	1x hydraulic pump	Pump the treated greywater in the nutrient solution mixing tanks
Results		**Results**	
Total dimension of the nitrification room	110 m²	Total dimension of the green walls	350 m²
Total volume of the urine influent	1204 L/day	Total volume of the greywater influent	76916 L/day
Reused treated urine	555 L/day	Reused greywater	26358 L/day
Total discharged treated wastewater: 50487 L/day			
Final COD concentration in discharged wastewater: 37 mg/L			

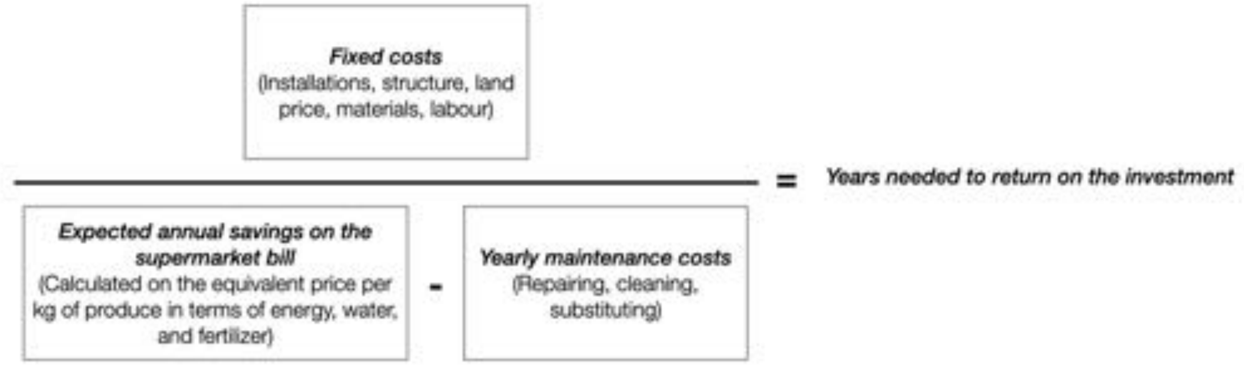
The wastewater treatment system coupled with two hydroponic production methods (the PFAL, and the integrated rooftop greenhouse) proved to be efficient in removing harmful pollutants in domestic wastewater, reaching optimal discharge standards. Furthermore, the decentralized wastewater treatment performed well in recovering almost all the nutrients and all the water required by the production systems.

Concerning the production results, both PFAL and the greenhouses were able to satisfy the local food demand of vegetables. However, the high energy costs related to the production of berries were considered a limitation in the production of fruit crops in the neighborhood. In this regard, further research is needed to find highly productive fruity crops that can be produced in narrow urban areas. Furthermore, the integration of Photovoltaic panels on top of the roofs of the cluster was crucial to dramatically reduce the energy costs related to indoor production.

Concerning costs, reusing treated greywater directly from the building blocks is a key strategy to reduce production costs. Further research is needed to properly assess the costs of the green walls, especially related to maintenance and day-to-day operations. Indeed, as of today it is still not clear how well greywater treating green walls can perform through time. In this sense, pilot projects and further experimentation on the field is necessary to precisely determine their life cycle. Labor costs resulted quite high for the operation of the rooftop greenhouses, however, they were calculated based on a worst-case-scenario assuming that all the rooftop surface would be cultivated. Assessing precise labor expenses is crucial to determine the economical sustainability of the project, as they have a high impact on production costs [50]. Nonetheless, considering the equivalent water, labor, and energy costs per kilogram of produce, the whole model performed well. In fact, with regards to these costs, each dweller could save up to 1112 €/year on its supermarket bill (meaning that a Cluster composed by 860 people would save approximately 1 million €/year) . Further research is then needed to assess the costs related to:

- Energy and installation of the decentralized urine treatment
- Energy and installation costs of the hydraulic pumps
- Retail price of the greywater collecting tanks and the nutrient solution mixing tanks
- Installation of the green wall with regards to the costs of the plants, the structure, the substrate, and the maintenance
- Structural costs of the greenhouses and the PFAL
- Installations in the production systems such as LED lamps, HVAC system, boilers, CO_2 gas tank, etc…
- Potential land costs

Once all the costs related to the the food production systems and the wastewater treatment are known, it is possible to calculate how much time is needed for the inhabitants of the BIA cluster to return on the investment by dividing the fixed costs with the difference between the yearly maintenance costs and the estimated yearly savings on the food retail prices:



If the yearly maintenance costs are higher than the expected annual savings on the food retail price (1 million €/year in the case of the Sluisbuurt), the whole BIA system would be economically unsustainable for its inhabitants.

In conclusion, the development of a BIA model for Cluster 2 in the Sluisbuurt represents just an example of a broader methodological approach that could be applied to several locations in different countries. However, as repeatedly stated in Chapter 3 and 4, BIA projects similar to this one proposed for Amsterdam are better suited for a particular geographic area. The application to other climatic zones, with different weather conditions and different culture, would need to adjust several of the considerations done for this project. However, the four steps described in the methodological approach seems to be a good starting point for the development of every BIA project that aims to integrated wastewater treatment with the hydroponic production systems. Finally, further research on the presence of harmful pathogens and bacteria in the plants, such E.coli and Novovirus, should be done. In this sense, the results that were found in the literature seemed to be promising [62][75][77], but still not conclusive.

4. Conclusions

The whole section 3 of this chapter was dedicated to the application of the proposed methodology to a selected case study in Amsterdam: the new Sluisbuurt neighborhood. The application of the methodological approach was needed to assess the strengths and the limitations of the proposed methodology.

The first thing that was noticed during the application of the methodology to the selected case study was that each step, each decision, was strictly connected to all the others. In this sense, the methodological approach subdivided in consecutive steps was found to be too rigid. Thus, a more fluid, interconnected methodology is highly recommended. However, the rigid structure of the proposed methodology helped focusing on the development of the BIA mode, creating the conditions to address all the initial issues and extrapolate the wanted results. Finally based on the experience acquired during the development of this chapter and of the BIA model for the Sluisbuurt, it is possible to assess advantages and disadvantages of the initially proposed methodological approach, and assess a broader methodology that could help architects, planners, and developers in the design of BIA projects.

Advantages

- The rigid structure helped in the development of the BIA project for the Sluisbuurt and in extrapolating the wanted conclusions.
- The methodological approach divided in four step appeared to be easily generalized and applicable to other scenarios.
- Selecting the crops as a first step proved to be crucial to determine the project set-ups. Knowing the crops means knowing the production capacity, which influence the sizing of the production spaces, and the plants' requirements in terms of water and nutrients. Thus, selecting the crops as initial step will provide the precise inputs to assess the quantity and quality of treated wastewater.

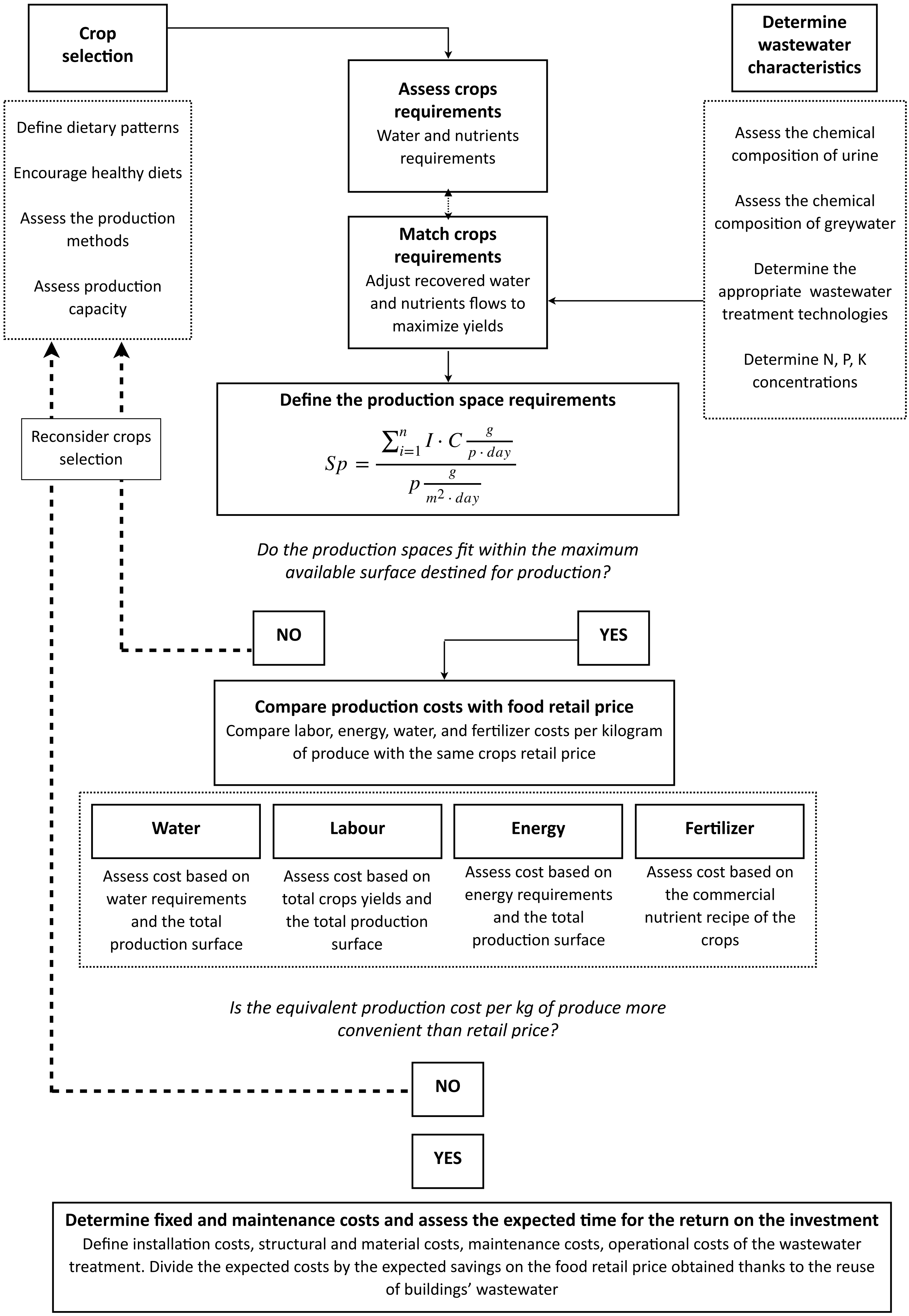
Disadvantages

- The rigid, cascade structure of the four steps forced several reconsiderations on previous findings. For instance, right in the middle of the second step it was noticed that berries production was unsustainable, therefore, all initial assumption needed to be changed to adjust to the new set-up.
- Determine the food production surface as a second step seemed too binding. Due to the great amount of water and nutrients contained in wastewater, it would have been possible to size the production spaces in order to better exploit reclaimed resources.
- The data acquired during the development of the first three steps constituted the inputs to assess the feasibility of the whole 'BIA - Wastewater treatment' system in the fourth step. However, the given data appeared in a sparse order. In this sense, the proposed methodological approach wasn't able to collect inputs on each step in an optimal way. Therefore, a more compact, organized methodology should be adopted.
- However effective, the development of a broader methodology should be more efficient, connecting the steps in order to limit the amount of calculations needed to extrapolate results.

Based on the considerations reported above, it emerged clearly that, however effective, the proposed methodology had seemed too dispersive to be easily applied on a broader scale. In this sense, thanks to the experience acquired during the development of the BIA model for the Sluisbuurt area, it was decided to adjust the initially proposed methodological approach.

The final and recommended methodology is shown in the flow chart below (Fig. 23), and proposed a more comprehensive approach, where each phase of the project is interconnected with the others.

Fig. 23: Final recommended methodology for the development of BIA model with integrated wastewater treatment



Source: *Own work*

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Supplementing Material

European Commission

Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

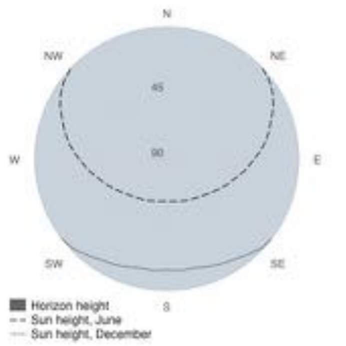
Provided inputs:

Latitude/Longitude:	52.370, 4.908
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed:	441 kWp
System loss:	14 %

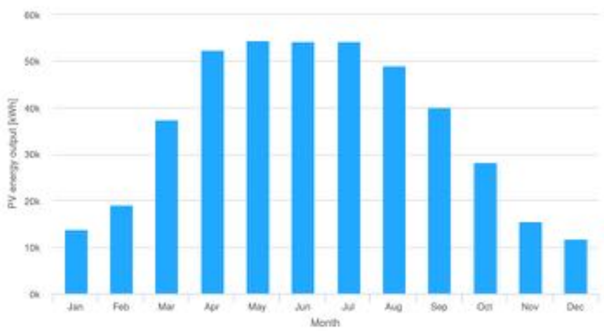
Simulation outputs

Slope angle:	35 °
Azimuth angle:	0 °
Yearly PV energy production:	429914.1 kWh
Yearly in-plane irradiation:	1242.71 kWh/m²
Year-to-year variability:	19027.44 kWh
Changes in output due to:	
Angle of incidence:	-3.07 %
Spectral effects:	1.75 %
Temperature and low irradiance:	-7.51 %
Total loss:	-21.55 %

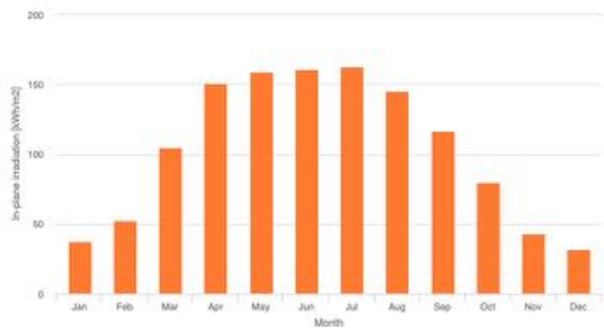
Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:



Monthly in-plane irradiation for fixed-angle:



Monthly PV energy and solar irradiation

Month	E_m	H(i)_m	SD_m
January	13756.3	37.3	2284.1
February	19095.6	52.1	4030.5
March	37417.2	104.4	5100.6
April	52357.8	150.5	7725.4
May	54461.3	159.1	4821.5
June	54160.4	160.6	4484.2
July	54195.5	162.6	6402.1
August	48979.2	145.2	7380.5
September	40050.4	116.6	4636.1
October	28176.7	79.5	3569.6
November	15504.4	42.8	2899.3
December	11759.4	32.0	2510.8

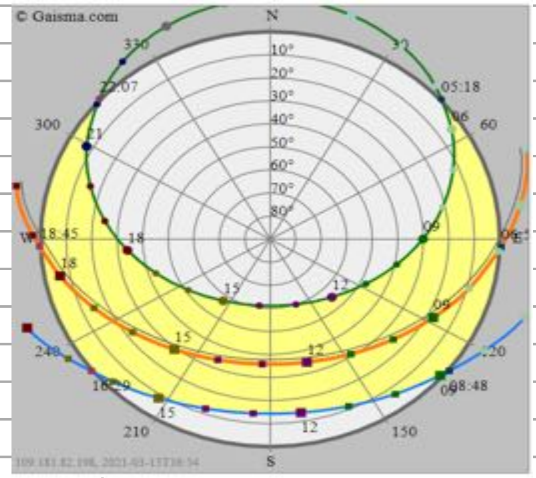
E_m: Average monthly electricity production from the given system [kWh].

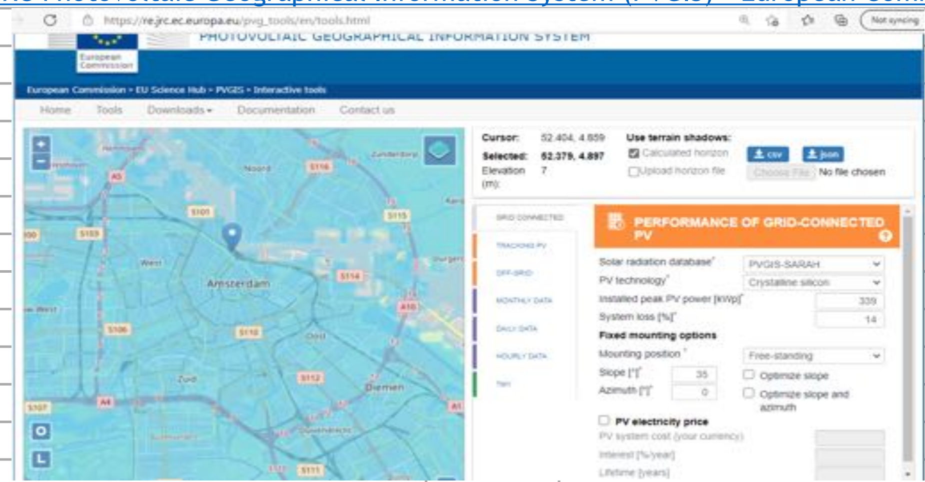
H(i)_m: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SD_m: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Report generated on 2021/03/21

1- Calculation of optimum amount of PV surface installed				
Exposed horizontal surface available for PV	3.900,0	m2		
PV characteristics			Common commercial cristalline	
Typical number of cell	72,0			
Typical length	2,0	m		
typical width	1,0	m		
Typical large PV panel size	1,9	m2		
Typical power crest/peak (PWc)	360,0	Wc		
Typical specific power crest	185,5	Wc/m2		
optimal angle (mid-summer midday)	35,0	degree	Gaisma.com	
winter solstice midday sun angle	14,0	degree	Gaisma.com	
summer solstice midday sun angle	60,0	degree	Gaisma.com	
Calculation of optimal footprint				
Typical surface covered	0,5			
footprint panel	1,6	m2		
Total footprint usable	1.950,0	m2		
surface of PV panel installed	2.380,5	m2		
Total Power Crest (or Peak Power) installed	441.664,1	Wc		
Total Power Crest (or Peak Power) installed	441,7	kWc		
2- Total maximum electric power that could be harnessed from sun			JRC Photovoltaic Geographical Information System (PVGIS) - European Commission (europa.eu)	
January	13.756,0	kWh		
February	19.095,0	kWh		
March	37.417,0	kWh		
April	52.357,0	kWh		
May	54.461,0	kWh		
June	54.160,0	kWh		
July	54.195,0	kWh		
August	48.979,0	kWh		
September	40.050,0	kWh		
October	28.176,0	kWh		
November	15.504,0	kWh		
December	11.759,0	kWh		
Total yearly	**429.909,0**	**kWh**		
Average daily sun energy harvesting			Average monthly sun energy harvesting	
January	443,7	kWh/day	January	13.756,0
February	682,0	kWh/day	February	19.095,0
March	1.207,0	kWh/day	March	37.417,0
April	1.745,2	kWh/day	April	52.357,0
May	1.756,8	kWh/day	May	54.461,0
June	1.805,3	kWh/day	June	54.160,0
July	1.748,2	kWh/day	July	54.195,0
August	1.580,0	kWh/day	August	48.979,0
September	1.335,0	kWh/day	September	40.050,0
October	908,9	kWh/day	October	28.176,0
November	516,8	kWh/day	November	15.504,0
December	379,3	kWh/day	December	11.759,0
Total daily average	**1.177,8**	**kWh/day**	**Total monthly average**	**35.825,8**





Annex 2: Sizing the MBBR reactor

Nitrifying MBBR (Moving bed biological reactor)				
Key Design parameters	**value**	**unit**	**typical ranges**	**Notes / references**
1- Basis for design (flows and loads):				
Number of people covered in treatment work	860	person		
Specific urine collected per person per day	1,4	l/per/day		
Urine volume to be treated per day	1204	l/day		
Average continuous flow of urine	0,050	m3/h		
Urine Ammonia load	7740	g NH3-N/day		
Urine BOD load	3405	g BOD/day		*Tervahauta, Taina [63[*
Urine BOD load	3,4	kg BOD/day		
2- Reactor design volume according to Thames Water Asset standard AM-DES-WWT-WWT 4.6b (IFAS dec 2017):				
Specific protected surface area of media	800	m2/m3	150 - 1200 for plastic media 4000 - 7000 for porous media	TW WWT 4.6b
Max organic surface loading rate	10	g BOD/m2/day	10-13 (@25oC)	
Max F/M ratio	0,15	kg BOD/kg MLSS/day	0.15 - 0.20	TW WWT 4.6b
MLSS Concentration	2500	kg MLSS/m3	2000 - 3500	TW WWT 4.6b
Min Retention time	2,5	h	2h - 5h	TW WWT 4.6b
Biomedia filling fraction	67	%	50 - 67	TW WWT 4.6b
Maximum media ammonia loading rate	0,7	g NH3-N/m2/day		TW WWT 4.6b
Min Surface Media required for nitrification	11057	m2		
Min reactor volume required to maintain F/M	0,009	m3		
Min media volume to maintain organic surface loading	0,426	m3		
Min media Volume required for nitrification	13,8	m3		
Min volume required to maintain RT	0,13	m3		
Min volume required to allow for media expansion	20,6	m3		
Conclusion: nitrifying reactor volume required	**20,6**	**m3**		
3- Reactor design volume according to eThekwini pilot plant:				
Urine Ammonia concentration	1800	mgN/l		Vuna Final Report 2015
urine volumetric flow	50	l/day		Vuna Final Report 2015
Assumed volume urine per person per day	1	l/p/day		only for eThekwini
Number of people urine equivalent	50	persons		
Urine ammonia load	90	gNH3-N/day		
max nitrification rate	800	mgN/l/day		Vuna Final Report 2015
Min nitrification rate	400	mgN/l/day		Vuna Final Report 2015
minimum reactor volume @ max nit. rate	112,5	liters		
minimum reactor volume @ min nit. rate	**225**	**liters**		
Infered specific Reactor volume design parameters 1:	5	liter/person		
Infered specific Reactor volume design parameters 2:	2,5	liter/(gN/day)		
Volume reactor design parameter 1	4	m3		
Volume reactor design parameter 2	19,35	m3		
Conclusion: Total nitrifying reactor volume required	**19,4**	**m3**		
Dimension for 2 reactors:				
assumed column height	**3,0**	**m**		
diameter internal column	**2,0**	**m**		
Number of reactors:	**2**			
4-Conclusion: size of nitrifying MBBR column				
Using Vuna final report 2015's results on nitrifying MBBR reactor to turn ammonia in urine into a staliblized ammo-nitrate (fertilizer),				
we have compared sizing of the reactor using conventional Nitrifying MBBR design in waste water treatment industry.				
We found similar reactor volumes (20.6 m3 vs 19 m3). However, waste water industry is aiming to treat most of ammonia, whereas the Vuna				
project is only interested to convert half of the ammonia load into nitrate, to form a stabilized ammo-nitrate fertilizer at pH around 6.5				
The comparison was however helpful to gain confidence in sizing of the nitrifying column				
In conclusion, to treat 860 residents worth urine into ammo-nitrate fertilizer, we would need two reactors of 2.5 m high and 2.2 m diameter				

Annex 3a: Macronutrients concentration in urine-based fertilzier. Calculations to match P requirements

1- Nutritive solution specifications		**Leafy Green**		**Fruit vegetable**		
water requirement	l/day	2365		5456		
N concentration	mg/l	173,6		295,4		
P concentration	mg/l	34,1		48,4		
K concentration	mg/l	281		421		
N requirement	g/day	411		1612		
P requirement	g/day	81		264		
K requirement	g/day	665		2297		
2- Available solutions:						
Stabilized urine						
Volume available	l/day	1204		1204		
N concentration	mg/l	6429		6429		
P concentration	mg/l	571		571		
K concentration	mg/l	2000		2000		
Mass N available	g/day	7740		7740		
Mass P available	g/day	688		688		
Mass K available	g/day	2408		2408		
Grey water						
Volume available	l/day	75673		75673		
N concentration	mg/l	12		12		
P concentration	mg/l	4		4		
K concentration	mg/l	8		8		
3- Nutritive solutions prepared from urine and grey water					**Total**	**used (%)**
Volume urine	l/day	126		429	**555**	**46%**
Volume grey water	l/day	2239		5027		
Total volume made	l/day	2365		5456		
N concentration	mg/l	354		516		
P concentration	mg/l	**34**		**48**		
K concentration	mg/l	114		165		
4- Conclusion: comparison of nutritive solution required and solution prepared						
Using Newton iterative method in excel						
		Leafy Green		Fruit vegetable		
Nutritive solution:		ideally required	prepared	ideally required	prepared	
water requirement	l/day	2365	2365	5456	5456	
N concentration	mg/l	173,6	354	295,4	516	
P concentration	mg/l	34,1	34	48,4	48	
K concentration	mg/l	281	114	421	165	

Annex 3b: Macronutrients concentration in urine-based fertilzier. Calculations to match N requirements

1- Nutritive solution specifications		**Leafy Green**		**Fruit vegetable**		
water requirement	l/day	2365		5456		
N concentration	mg/l	173,6		295,4		
P concentration	mg/l	34,1		48,4		
K concentration	mg/l	281		421		
N requirement	g/day	411		1612		
P requirement	g/day	81		264		
K requirement	g/day	665		2297		
2- Available solutions:						
Stabilized urine						
Volume available	l/day	1204		1204		
N concentration	mg/l	6429		6429		
P concentration	mg/l	571		571		
K concentration	mg/l	2000		2000		
Mass N available	g/day	7740		7740		
Mass P available	g/day	688		688		
Mass K available	g/day	2408		2408		
Grey water						
Volume available	l/day	75673		75673		
N concentration	mg/l	12		12		
P concentration	mg/l	4		4		
K concentration	mg/l	8		8		
3- Nutritive solutions prepared from urine and grey water					**Total**	**used (%)**
Volume urine	l/day	60		240	**300**	**25%**
Volume grey water	l/day	2305		5216		
Total volume made	l/day	2365		5456		
N concentration	mg/l	175		294		
P concentration	mg/l	**18**		**29**		
K concentration	mg/l	59		96		
4- Conclusion: comparison of nutritive solution required and solution prepared						
Using Newton iterative method in excel						
		Leafy Green		Fruit vegetable		
Nutritive solution:		ideally required	prepared	ideally required	prepared	
water requirement	l/day	2365	2365	5456	5456	
N concentration	mg/l	173,6	175	295,4	294	
P concentration	mg/l	34,1	18	48,4	29	
K concentration	mg/l	281	59	421	96	

Conclusions and Summary of the research

The general objective of this thesis was to assess the benefits of integrating off-soil, advanced food production methods into the architectural design. In this regard, a review of several fields of application of Urban Agriculture, as well as several technologies, has been carried on in the first part of the research. The literature review helped to identify the framework of this thesis, which eventually focused on how advanced integrated food production systems could enhance circular flows of resources between the architectonic enclosure and the production areas. In this sense, the thesis focused primarily on studying the interactions between the hydroponic systems and the building with regards to wastewater treatment. This choice was taken for three main reasons:

- To our knowledge, still, little research has been done on the hydroponic system as the final decentralized treatment for wastewater.
- Using the hydroponic system as decentralized final wastewater treatment can highly contribute to safely discharge domestic wastewater to the sewer.
- Domestic wastewater is rich in macronutrients such as N, P, K fundamental for plants growth. If properly recirculated from the buildings to the hydroponic system, wastewater can be converted from waste into input for production.

The research concluded that it is theoretically possible to reuse domestic wastewater for hydroponic production, representing a substantial gain in water and fertilizer utilization. Nonetheless, further research on operational costs and the potential presence of harmful pathogens in the reclaimed water should be done to safely apply the system in real-life projects.

However, to determine the specific focus of the thesis, an extensive literature review was needed to define the fields of application of UA, as well as the geographic area of intervention. Therefore started by analyzing what is Urban Agriculture, and how it could be integrated within the architectonic environment.

Progressive steps of the research

Urban Agriculture presents a great potential for the development of new circular and sustainable planning strategies for future European cities. For this reason, architects and planners are key players in developing design models that could implement and integrate UA practices within the city borders. Therefore, this thesis started from the consideration that UA is not just a food-related practice, but as a comprehensive and holistic set of initiatives that can improve the overall sustainability of highly dense urban settlements. In this scenario, **Chapter 1** of this thesis describes the current state of UA with regards to its history and its potentiality. The objective of Chapter 1 was to acquire a general knowledge on the topic, focusing on the benefits and the challenges of UA projects. What emerged from the first chapter was that UA has a myriad of applications that differ based on several parameters such as:

- Objectives of the project
- The users to whom the project is addressed to
- The investments required to set up the project
- The geographical location of the project

Based on the considerations done in the first chapter, **Chapter 2** analyzed the different fields of application of UA, specifically addressing the issues of soil-less Urban Farming. Indeed, the possibility to integrate food production methods within architectural buildings is probably the practice that mostly relates to the architectural world. To this concern, Chapter 2 limited the conceptual scenario of intervention to two specific sub-practices of UF: i) Building-integrated agriculture (BIA), and ii) Zero-acreage Farming (ZFarming). Today, when browsing on architectural magazines is easy to bump into projects that propose the integration of food and vegetation in new buildings. However, most of the time it is very hard to assess the actual feasibility of these projects, and what is worse, it is even more difficult to understand the benefits they can bring. Sometimes it appears that both food and the greenery are used by architects to just sell a better picture of their project instead of seriously addressing social and environmental issues. In this context, for a better understanding of BIA and ZFarming concepts, it was decided to review 24 state-of-the-art projects designed and developed by famous architecture firms that addressed different scales of the architectonic design:

- Urban districts and neighborhood
- Urban outdoor installations
- Buildings: rooftops and facades
- Indoor spaces and product design

The analysis of the state of the art proved very useful in defining objectives and strategies of UF projects integrated with the architectural environment. In this regard, specific focus was given on circular economy principles, and how food production could support and improve the design of a new circular green architecture. Based on these considerations, **Chapter 3** analyzed the hydroponic technologies that are permitting the development of BIA and ZFarming projects, assessing their potential and their functionality. With regards to the soil-less technologies analyzed in the first part of the chapter, the thesis explored the relations between those technologies and the built environment, assessing the strategies for proper integration of food production methods within buildings. Due to the high technical requirements, and the necessary knowledge needed to operate such systems, it was possible to determine the geographical and climatic area in which BIA projects are expected to be more easily developed, identifying in the Center-Northern European context the hub for their experimentation. Two main cities were selected as a possible game-changer for the development of BIA projects, namely London and Amsterdam. The analysis of their urban plans was crucial in defining the focus of the research mentioned at the beginning of this summary: use the food production system as a way to recover waste and use them as inputs for the production of food. Subsequently, **Chapter 4** identified the potentiality of integrating advanced production systems within buildings, specifically focusing on how to recover domestic wastewater and use it as input for food production. The whole chapter is a review of the best available technologies for wastewater treatment coupled with hydroponic production, focusing on the impact that treated wastewater has on the plants. After an extensive literature review, it was possible to assess the conditions for wastewater recovery, analyzing source separating systems, and defining the best streams to be treated for hydroponic production. In this sense, the research exclusively focused on urine and greywater, as the former has the highest content of macronutrients, while the latter provides a great amount of water needed in the nutrient solution. This analysis showed that treated wastewater can be used as a nutrient solution in hydroponic systems, reporting different results from several recent experiments. To properly verify the results reported in the literature, **Chapter 5** shows a complete wastewater cycle in a selected case study located in Amsterdam. The project area was chosen as a sample of the new development strategies carried on by the municipality, providing inputs such as:

- Total number of inhabitants
- Urban density
- Dimensions of the area of intervention
- Building requirements of the plan

Thus, the selected area worked as a canvas where to assess the feasibility of using wastewater treatment coupled with hydroponics and to define a specific methodology that could aid the workflow of architects and planners in developing this specific type of project. The proposed methodology worked in four steps:

- Step 1: Selecting the crops
- Step 2: Define the production methods and their spatial footprint
- Step 3: Assess local wastewater characteristics
- Step 4: Verify the feasibility of the system

Developing the proposed methodological approach was crucial to calculate the number of nutrients and water recovered from the project area, based on the number of inhabitants and the wastewater characteristics. Results showed how wastewater can potentially supplement the production with a high concentration of nutrients and with all its water needs. However, due to the high amount of N in the urine, it is possible to expect lower yields in urban areas when reusing wastewater as a main (if not solely) source of nutrients. Furthermore, it was noticed that the proposed methodology resulted too rigid. However, thanks to the experience acquired during the application of the proposed methodological approach to the area of intervention, it was possible to conclude the chapter with a different broader methodology that could be used as a reference for further development of BIA projects with regards to wastewater treatment in multiple scenarios.

In conclusion, this thesis extrapolated some interesting results concerning how much food can be produced in urban areas and how much water can be saved by producing this food. The data concerning high-tech food production calculated in this thesis shows that PFALs are advantageous only if they can guarantee a much higher production of food than the greenhouses. For this reason, berries were eventually discarded as they required an enormous amount of energy for such a reduced amount of produce. However, when choosing the right crops, the food produced in a joint effort between PFALs and iRTGs might constitute a real competitor to supermarket commercial food in dense urban environments. Indeed, based on the expected consumption data and the reported yields of the crops, the food production system in Cluster 2 was able to exceed the expected local food demand, **producing roughly 160% more of the expected (and desired) consumption**. On a broader scale, considering that Amsterdam will build 52.500 homes within the city boundaries by 2025, it would be possible to produce enough vegetable food for this whole new Amsterdam population by implementing BIA projects on 32.800 new homes. **Assuming a similar urban density of the Sluisbuurt - 150-200 households per hectare - a total of 164-220 ha of would be needed to feed the new 'Amsterdammers'**.

Furthermore, the proposed system is able to produce food by recycling fundamental resources such as nutrients and water. What emerged from the calculation in this thesis is that the considered building blocks already produce way more water and nutrients than what is required by the system, with plenty to spare. Indeed, **54% of the treated urine appears to be in excess**, for which this research calls for new allocating solutions in future studies. Concerning water, **35% of it can be safely recycled and reused both as irrigation water in the rooftop greenhouses or as washing water for the dwellers of the building blocks**. Moreover, the calculations in Chapter 5 theoretically demonstrate that mixing the recycled water with the treated urine can constitute a viable alternative to commercial fertilizer, even though the nutrient solution might need further adjusting. In this regard, the dilution calculations were made to match the P content of the urine-based solution to the P content of the commonly used commercial fertilizer. However, the macro-nutrients content in the urine-based fertilizer will allow a different dilution calculation to match the N content of the commercial fertilizer, in case further test results would show a worsening in plant growth due to the higher N concentration in the nutrient solution. The possibility to match the concentration either of P or N in the urine-based fertilizer makes it very flexible to several uses and seems to constitute a real alternative to commercial chemical fertilizers.

Future development of the research

Based on the results of this thesis further research should be done on the following topics:

1. Concerning the production systems:

- Study the possibility to limit heating and cooling by exchanging thermal flows between the production systems and the residential building.
- Study the possibility to increase CO2 concentration in the greenhouses by redirecting the CO2 from the building to the production spaces. Similar studies were already conducted in Barcelona at the ICTA-ICP office building. However, since CO2 concentrations in residential buildings are higher at night while plants mostly need CO2 during the day, new ways to properly exploit the exchange of CO2 in residential buildings must be researched.

2. Concerning the use of treated wastewater as the nutrient solution:

- Assess the presence of harmful pathogens and bacteria in the treated wastewater. Some of the reviewed literature demonstrated that the content of pathogens in their field experiments was very little and fit within the regulation for safe consumption. However, when using treated wastewater as the nutrient solution, specifically tailored experiments regarding the possible presence of pathogens in the treated wastewater should be done.
- Assess the loss in yields due to the higher concentration of N in treated urine. When diluted, N concentrations in treated urine can drop to match crops requirements. However, a high reduction in N concentration causes the reduction of also P and K concentration. Therefore, to match N concentration, the contribution of P and K in the treated wastewater would be minimum to plants growth. On the other hand, when diluting urine to match P concentrations, the nitrogen present in the nutrient solution was way higher than the nitrogen contained in commercial fertilizer. Thus further research on how to remove the excessive N in the nutrient solution should be done to maximize yields when using urine-based fertilizer.
- Furthermore, when diluting urine to match plants' requirements, a part of the treated urine needs to be discharged. Even if the treated discharged urine has a low content of pathogens (therefore it doesn't constitute health or environmental hazards), it seems a waste to treat high amounts of urine just to use less than half of it. In this sense, further research on how to use the treated urine, or how to optimize the nitrification reactor to treat just the right amount of urine must be done.
- This research focused only on macronutrient concentration in urine-based fertilizer. Results of other field experiments demonstrated that tomatoes grown with urine-based fertilizer showed reduced yields due to the lack of Calcium in the nutrient solution. Therefore, more research on the content of micronutrients and the complete composition of urine-based fertilizer should be done.

3. Concerning costs:

- In this research, the cost assessment was done concerning water, energy, and labor. Due to the different ionic forms of urine-based fertilizer, it was found very imprecise to assess the amount of money saved on fertilizer. Deeper research must be done to understand fertilizer savings based on the concentration of the nutrient in urine-based fertilizers.

- Fixed costs were not taken into consideration in this research. Thus, to properly assess the final costs of the BIA project, it is important to determine land costs, installation costs, and maintenance costs. Further research in this sense must be done if the real economic feasibility of the projects wants to be assessed.
- Energy operation costs of the wastewater treatment were not assessed. The chosen technologies for urine treatment work at high temperatures and require not negligible energy inputs. To assess the economic feasibility of the treatment, proper research on energy consumption of the systems should be done.
- Finally, this research misses a proper LCA analysis, which will be fundamental to assess the life span of the system and determine its actual capacity to make revenue. Further research on the LCA might provide new fundamental insights that will eventually lead to the construction and the completion of the integrated food production system proposed in this thesis.

Furthermore, more in-depth research should be conducted on the beneficial impacts that the integration of advanced food production systems in the urban environment might bring to cities. For instance, it has been reported many times in this thesis, as well as in the cited papers, that a reduced concentration of COD and Nitrogen in the effluent water will have a positive effect on water eutrophication in urban areas. However, future researches should address this issue, quantifying the actual benefits of the reduction in COD and N in the effluent water caused by the integrated hydroponic systems. Indeed, this thesis explored the direct effects that the integrated hydroponic-wastewater recovery system has on the urban environment (i.e. energy costs and efficiency, food production, water recycling), but couldn't explore the indirect possible environmental benefits that a wastewater-recovery, locally-grown and high-tech food system may have on the territory.

In this sense, this thesis hopes to provide the right set of instruments to bring the research few steps forward towards the analysis and the quantification of the possible indirect benefits that the system hereby proposed will have on the local and even global environment whether implemented and developed. In conclusions, based on the subject proposed in this thesis and on its results, indirect environmental benefits quantification should focus on:

- Possible reduction in the water eutrophication in the urban areas
- Heat Island effect reduction thanks to the increasing presence of plants and consequent evapotranspiration on top of the urban buildings
- CO_2 emissions reduction due to plant's CO_2 absorption in urban areas

Conclusions

On a final note, what emerged from the research is that the application of advanced food production systems in residential buildings for the development of sustainable BIA models is a completely new language for architects. In this sense, architects that are seriously willing to implement these systems are required to understand and speak this new language to communicate with other professionals and practitioners like engineers and agronomists. What was clear during the development of this thesis is that architects alone would struggle to implement these systems without the help of expert agronomists that can address the real issues of advanced urban food production. For this reason, this thesis also wants to be a theoretical and practical guide for those architects that are interested in understanding a new architectonic typology, with its own rules and its own language. In this sense, a special thanks would go to professor Francesco Orsini, of the University of Bologna, that was able to guide me and introduce me to this new world, made of plants and organic matters instead of walls and beams. A difficult world for sure, but a world that we should all hope for our future.

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