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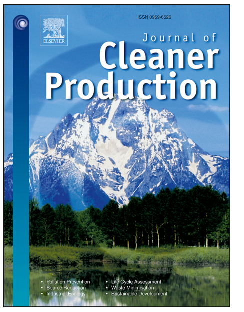

Mobile solution for digestate transformation to high added-value products

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Mobile solution for digestate transformation to high added-value products

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Digestate liquid fraction derived from four biogas plants fed with different organic sources (animal manure, mixed waste, agricultural waste and urban sewage sludge) was treated using a series of processes that were integrated on a mobile platform. These processes included microfiltration and ultrafiltration for the removal of solids and large organic molecules, selective electrodialysis for the recovery of nutrients, UV ozonation to selectively oxidize pharmaceuticals and reverse osmosis for clean water production. Results showed that 48-58% of the digestate could be recovered as water that can be used for irrigation or process needs, while 51-67.8% of nitrogen could be recovered by the selective electrodialysis process and used for fertilizer production tailored to farmers' soil and crop requirements, aiming to replace fertilizers from non-renewable minerals. Applying UV ozonation for the oxidation of pharmaceuticals before the nutrient recovery step was found to be twice as effective as applying it after nutrient recovery. The solid fractions of various digestates were applied as fertilizers for lettuce grown in pots, with the digestate from agricultural and food waste origins giving some of the best yields with the lowest GHG emissions. The solid fraction from sewage sludge digestate produced the highest yields in lettuce growing, but also resulted in much higher GHG emissions than the other fertilizers. A business model for the implementation of the developed technology in three operational scenarios concluded that a mobile solution shared between small anaerobic digestion plants in a region could have a five-year return on investment of 41.6% and a payback period of 1.96 years.

1. Introduction

In recent decades, the transition to a circular economy and environmentally friendly waste management has been increasingly seen as imperative. Recovering nutrients from waste and using them in agriculture is an alternative and eco-friendly approach to replace chemical fertilizers which involve energy intensive or non-sustainable production methods and high greenhouse gas emissions (GHG) [1]. Anaerobic digestion (AD) is a process used in biogas plants to convert organic waste (municipal sewage sludge, animal waste, food waste, and agricultural waste) that would otherwise end up in landfill, into a renewable energy carrier, biogas. The AD biogas plants also generate digestate as a by-product, which is a rich source of nutrients and may be used to enhance soil with both inorganic and organic elements. This is viewed as an alternative, environmentally-friendly approach for the replacement of chemical fertilizers and soil conditioners.

However, digestate has a variable chemical composition stemming from changes in the raw materials used as feed in the anaerobic digesters of the biogas plants [2], making standardized application difficult. Direct application to the soil may cause unregulated leaching of nutrients (nitrogen, phosphorus, or potassium) into surface and groundwater, leading to eutrophication and contamination [3]. Moreover, improper application of liquid digestate, such as surface spreading, can be a significant source of GHG and ammonia emissions, risking a reduction in its environmental performance [4]. Digestate may also contain pollutants such as pharmaceuticals and heavy metals when derived from manure or sewage sludge, leading to soil contamination and the development of antibiotic-resistance genes in bacteria [5]. Furthermore, a high microbial load in digestate can render its disposal in soil hazardous to public health [6]. Another factor to consider is the large volume, due to its ~95% water content, which raises the cost of transportation from the biogas plants to the fields or disposal sites. The ongoing demand for environmental protection and stiffer regulations on the application of fertilizers and soil conditioners necessitate the development of innovative digestate treatment processes that strive to comply with standards in the most cost-effective and environmentally friendly manner possible [7], [8].

Separating digestate into liquid and solid fractions, using methods such as screw presses or centrifuges, is currently the most commonly deployed process for digestate management. This separation reduces the volume and facilitates transportation [2]. For the liquid fraction treatment, ammonia stripping for nitrogen (N) recovery and membrane separation have been proposed. Furthermore, alternative methods such as electrodialysis, membrane distillation, and microbial cell recovery have been investigated but have yet to be implemented on a large scale [9], [10]. Even more intensively, membrane filtration processes have also been studied in digestate treatment [11], [12], [13], but they suffer from low nutrient selectivity and the inability to remove contaminants [14], [15], especially organic ones, even when employing a combination of multiple processes [16].

The present work aims to investigate a technology for the processing of digestate in a more compact way in order to: (i) reduce the overall volume of the liquid fraction, (ii) selectively recover nutrients from the liquid fraction of the digestate, (iii) neutralize antibiotics and other pharmaceuticals and (iv) produce clean water. The processes employed to this end were microfiltration, ultrafiltration, selective electrodialysis, advanced oxidation, and reverse osmosis. Various process-derived digestate fractions were used as fertilizers in greenhouse trials for the cultivation of lettuce. Besides the technical and greenhouse demonstrations, a business model considering three different exploitation models for the technology was developed, enabling calculation of capital expenditures (CAPEX), operating expenses (OPEX) and return on investment.

2. Materials and Methods

2.1. Description of experimental campaigns

2.1.1. Process feed-Digestate

The technology was applied to the liquid fraction of anaerobic digestate that was derived from four biogas facilities, that treat different feedstocks at mesophilic conditions and have different operational capacities. Information related to the biogas plants and digestate production is given in Table 1.

Table 1. Biogas plant operation and specifications.

	Manure case	**Mixed waste case**	**Agricultural waste case**	**Wastewater Treatment plant (WWTP) sludge case**
Location	Kozani, Greece	Oreokastro, Greece	Latina, Italy	Xghajra, Malta
Feedstock composition	Corn silage, animal faeces, urine and manure (including spoiled straw)	Animal waste (15%), agricultural waste (5%) and food waste products (80%)	Cereal silage (maize, sorghum, triticale, barley, oat) (20-25%) agro-industrial by-products (75-80%)	Sludge from treated mixture of urban and farmyard wastewater mixed with urban waste

				in the sewer collection network
Annual feedstock capacity	21900t	66000 t	24000 t	243000 t
Electricity generation	100 kWe	999 kWe	999 kWe	1000 kWe
Annual digestate arisings	20805 t	63220 t	20000 t	7220 t
Digestate separation	Screw press	Screw press	Screw press	Centrifuge

A first stage solid-liquid separation was performed in all biogas plants and the liquid part of the digestate was further processed through the array of equipment that is detailed below and was integrated into a trailer, which enabled an additional flexibility of the process for transportation to the biogas plants' sites, as well as the setting-up of the basis for a potentially shared commercial exploitation model.

2.2. Equipment description

A microfiltration (MF) unit consisting of four bag filters (made of polyester) in cascade arrangement, contained in 20" big blue filter housings, was used for the removal of coarser particles. Bag filters with various pore sizes were used in the experiments ranging from 800 to 1 μm fed by a centrifugal pump at flowrates of up to 1200 L/h and pressures up to 25 psig. At the next step of solid-liquid separation, an ultrafiltration (UF) system (SolarSpring GmbH, Germany) was used, consisting of two dead-end tubes fitted with 0.9 mm bore hollow fiber membranes, having 20 nm pores and an effective area of 6 m^2 each. The purpose of these two units was to remove as many suspended solids as possible before the digestate was fed to the more sensitive units that followed.

A selective electrodialysis (SED) unit (PCCell GmbH), Germany, described in previous communications [7]) was employed for the separation of nutrient ions from the filtered digestate. The unit is centered around a 25 cm x 25 cm cell (ED Q380) containing twenty cells, each consisting of standard anion and cation exchange membranes (AEMs and CEMs), as well as monovalent AEMs and CEMs. These were arranged to enable generation of an anionic and cationic streams, alongside a monovalent one. Typically, at the start of the process, the feed tank was filled with 20 L of filtered digestate, while the product tanks, receiving the anionic, monovalent and cationic products streams, were filled with 10 L of a 1% NaCl solution. The cell operating voltage was kept at 30 V, while the liquid streams were circulated through the cell at 250 L/h. SED runs were terminated once the conductivity of the feed dropped below 1 mS/cm.

The advanced oxidation unit (UVOX Redox® WAPURE International GmbH, Germany) consists of a UV chamber constructed from PE100 HDPE, four UV lamps with a total power consumption of 800 W housed within a quartz tube, an O_3-air Xyclon injector device, complete with a booster pump, power module and relevant connecting cables. The set-up was equipped with a UV-compact measurement device that records UV transmittance at 254 nm passing through a thickness of 10 mm of liquid sample. The unit was used to selectively degrade pharmaceutical compounds from the filtered digestate.

The reverse osmosis (RO) system (SPECTRUM, UK) employed four spiral-wound membranes with a total active area of 8.36 m^2, capable of withstanding pressures up to about 14 bar. It was used to recover clean water following the preceding treatments.

Figure 1 presents the concept of the proposed technology, illustrating the key components and their interactions within the overall system. This diagram highlights the foundational principles behind the technology and how it is intended to function in a real-world application.

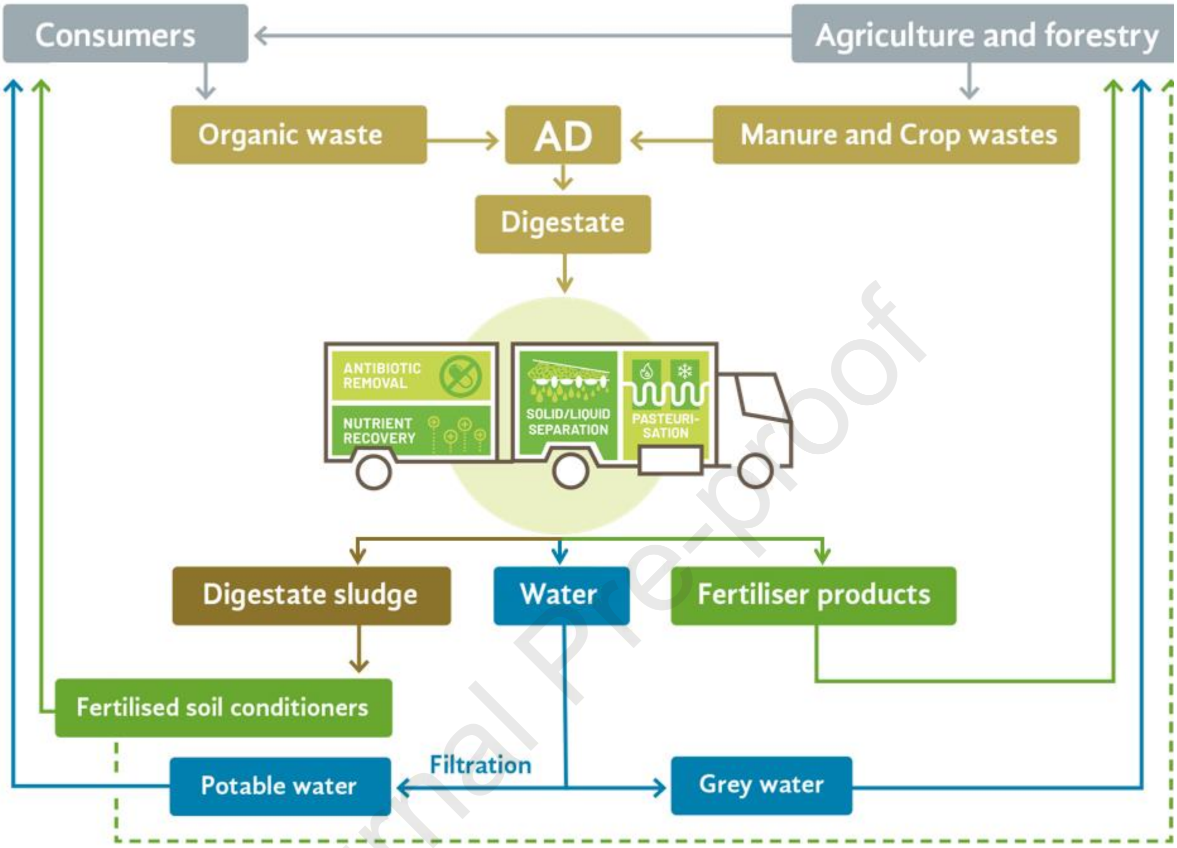


Figure 1. Conceptual design of the proposed approach.

2.3. Nutrient recovery

Following the separation of nutrients into three distinct products after treatment with SED, additional processing was necessary to acquire solid fertilizers. Blending these three individual products in the correct stoichiometric ratio has the potential to generate fertilizers like struvite or precipitates such as hydroxyapatite. In this investigation, an adjustment to the Mg/PO_4 ratio was made by introducing a suitable $MgCl_2$ solution.

For ammonia stripping, a 'scrubbing' method was employed using the air thermal stripping-acid absorption process. The setup comprises two vessels connected with a pump arranged in an open-loop system. The first vessel contains the SED concentrate from which ammonia is to be recovered, while the second one holds a solution of sulfuric acid (8% v/v). Throughout the process, the recovered ammonia undergoes absorption, forming ammonium sulfate ($(NH_4)_2SO_4$).

2.4. Antibiotics removal

These experiments were carried out in two of the four sites that were investigated in the current work; the case of digestate originating from manure processing (Biogas plant in Greece) and the case of the WWTP (Biogas plant in Malta). In order to evaluate the viability and choose the best sequencing of treatments in the trailer, UVOX was applied to the digestate streams after nutrient recovery and removing ions in in the case of the manure derived digestate and before nutrient recovery in the case of the wastewater processing digestate. In both sites the UVOX experiments were conducted in recirculating mode to treat at least 450 L per batch in 22 h. Hydrogen peroxide was added in some cases at ratios of 1.6 and 6.6 by weight to dissolved organic carbon (DOC). More specific experimental procedures can be found in previous work [22].

2.5. Crop growth test

Fertilization tests involved five solid fractions of digestate, along with a commercial organic fertilizer, with three replicates per treatment. The fertilizers tested were: digestate (solid fraction) from crop wastes (Latina, Italy – designated IT); digestate from food wastes (Warminster, United Kingdom – designated UK); digestate from municipal wastewaters (Xghajra, Malta – designated MT); digestate from pig manure (Kozani, Western Macedonia, Greece – designated GR); digestate from pig manure mixed with phosphorus (P)-enriched ultrafiltration concentrate (Kozani, Western Macedonia, Greece – designated GRENR); commercial organic fertilizer (Actiplus, Fertileva – designated COM); and control pots without fertilization (designated CON). Heavy metals and pathogen concentrations were analyzed and found to be lower than the Regulation (EU) 2019/1009 limits [17], with the exception of Ni concentration in the digestate from the WWTP biogas plant in Malta (64 mg/kg DM). The agronomic performance of the soil amenders was tested in a greenhouse environment at the Department of Agriculture, Food, Environment and Forestry (DAGRI) of the University of Florence. Lettuce (var. "Curly") was cultivated in pots 40 cm in diameter (one plant per pot) filled with sandy-loam soil (55% sand, 15.4% clay, and 29.6% silt) with 0.68% total N and 2.16% organic matter. Lettuce was chosen due to its short growing period, which facilitates the repetition of experiments. The fertilization rate was 60 kg $N \cdot ha^{-1}$, corresponding to the conventional fertilization rate used on farms and varying according to the different fertilizer types (Table 2).

Table 2. Elemental characterization of each treatment and corresponding amount per pot.

Parameter	IT	UK	MT	GR	GRENR	COM	CON
N content %	0.678	0.883	1.248	0.551	0.572	2.000	-
NH_4^+-N, mg/kg	1342	5404	2271	489	225	-	-
NO_3^--N, mg/kg	<100	<100	<100	33.1	<100	-	-
TOC, %	14.24	14.24	10.17	15.76	17.15	27.00	-
TP, g/kg	0.95	0.95	6.32	1.78	2.26	15.00	-
TK, %	0.49	0.49	0.06	0.17	0.55	2.1	-
Amount, g/pot	100.00	76.78	54.33	123.05	118.5	30.80	-

Lettuce was transplanted 28 days after the fertilizer materials had been mixed into the soil to ensure mineralization [18]. Transplanting occurred at the third true leaf unfolded phenological stage (stage 13 on the BBCH scale), following cultivation in peat. Morphological parameters such as plant diameter, plant height, and number of leaves were monitored throughout the growing season, while fresh and dry weights (after 48 hours at 80°C) were measured at harvest. The effect of the fertilizers was also evaluated from a physiological perspective by monitoring the chlorophyll content of the leaves and the Normalized Difference Vegetation Index (NDVI). Specifically, NDVI was used to assess the N content of the leaves and, consequently, the overall health status of the crop. GHG emissions were monitored using a portable gas analyzer (Innova 1512, Lumasense, DK) employing photoacoustic spectroscopy technology and the static chamber methodology [19]. GHG emission measurements were conducted three times per week. Monitoring occurred immediately after chamber closing (C0) and after 1 hour of gas accumulation (C60). GHG emissions were measured from the point of lettuce transplanting to harvest. GHG fluxes were calculated using the internal gas concentration difference (C60–C0), chamber area (314 cm^2), volume (9,420 cm^3), time of chamber closing, and the molar weight of each gas. The monitoring of GHG emissions was conducted starting from the transplantation of the lettuce to assess the emission dynamics from the soil during the cultivation phase. This may have led to an underestimation of emissions that could have occurred during the incubation period to ensure the mineralization of fertilizers. The GWP for each treatment was calculated using the IPCC reference coefficients from IPCC AR6 [20]. Yield-scaled emissions (GWP/yields) were normalized to a contribution per 1 kg of lettuce, without accounting for the amount of carbon stored in the leaves.

2.6. Physicochemical Analysis

Samples were taken from all streams of the integrated process, including the digestate, to monitor the operation and to enable mass balances to be derived across the different unit functions, alongside that of the overall process. The samples were stored in polypropylene bottles of appropriate size at 4 °C and analyzed within a week.

Total solids (TS) were measured according to 2540C standard methods. Total nitrogen (TN) was determined by the photometric method after digesting the samples with Merck Tests (DIN 38405-9). Phosphorus was analyzed as PO_4-P, using the vanadomolybdo-phosphoric acid colorimetric method and the absorption was monitored using a spectrophotometer (Spectroquant Pharo 300) at 470 nm. The determination of total organic carbon (TOC) and dissolved organic carbon (DOC) was performed using a TOC-L Analyzer (Shimadzu, Japan). All aforementioned analyses were performed according to Standard Methods for the Examination of Water and Wastewater [21] and have been described in detail in previous publications [22], [23].

Ion chromatography was employed for the determination of K^+, NH_4^+ and NO_3^- with a Prominence ion chromatograph (Shimadzu, Japan) equipped with an IC SI-52 4E anion column (Shodex, Japan), rinsed with sodium carbonate 3.6 mM as mobile phase at a flow of 0.8 mL/min, and an IC YS-50 cation column (Shodex, Japan), with methanesulfonic acid 4.0 mM as mobile phase at a flow of 1 mL/min.

Analytical methods used for the antibiotic removal trials can be found in a previous publication [24].

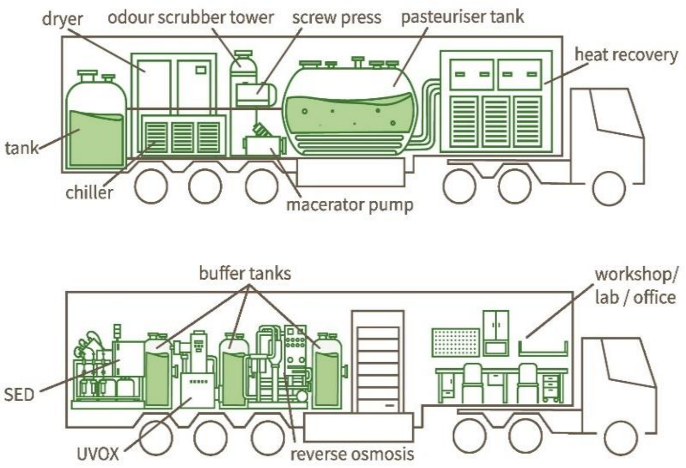
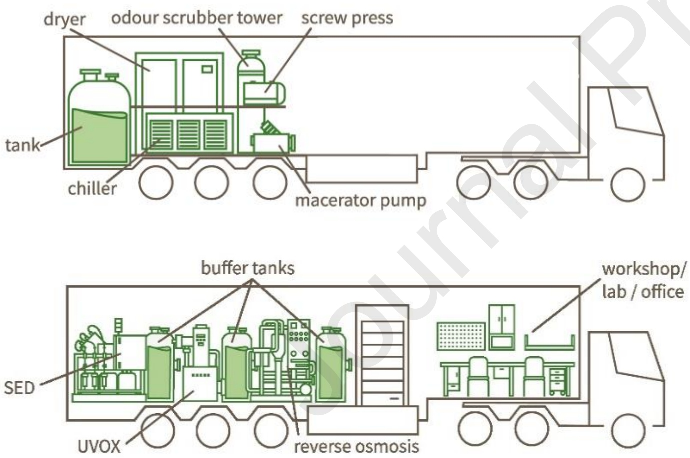
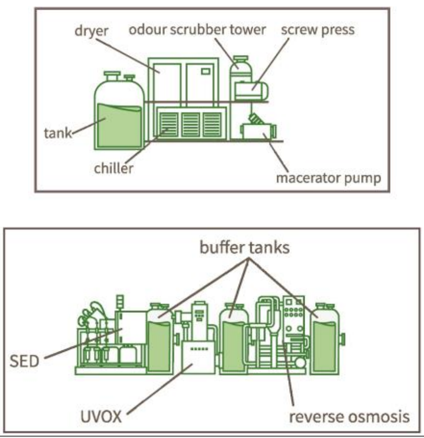
2.7. Business model

The business modeling tool was developed in an Excel spreadsheet and is designed to handle a range of input data, such as capacity, costs/revenue, and CAPEX/OPEX. It is used to compute financial performance metrics across different scenarios. The business modeling methodology and general assumptions are presented in the supplementary material.

For the purpose of the study, the digestate (prior to solid-liquid separation) was considered the process feedstock. This necessitated upstream process steps to enable pasteurization and fiber separation/drying, including a CHP unit for power generation, a pasteurizer tank, a macerator, a screw press, chiller and dryer units, and an odor scrubber tower, before proceeding to nutrient recovery, antibiotic/pharmaceutical destruction, and clean water generation. Both upstream and downstream functions would be operated within trailers (Trailer 1 for upstream functions and Trailer 2 for the remaining ones), that are collectively referred to as NOMAD when discussing the business model.

Three operational scenarios for exploiting the digestate management technology were explored (see Table 3). These scenarios are tested in the study using simulated fixed geographical locations, site conditions, technology deployment, process performance, and cost/revenue metrics to evaluate and compare each scenario.

Table 3. Different business case scenarios examined.

<table>
<tr><th>Scenario</th><th>Description</th><th>Typical Customer</th></tr>
<tr><td>#1

</td><td>Both trailers in operation
Assumes that both trailers are fully operational and that all features are used:
CHP
Pasteurizer tank
Macerator & screw press
Chiller unit & dryer
Odor scrubber tower
Microfiltration & ultrafiltration
Reverse Osmosis
Selective Electrodialysis
UVOX</td><td>AD sites with no on-site pasteurization and no available power on site (e.g. small AD plants). The AD site will likely have some storage space for digestate, and hence a mobile solution to occasionally service the site is suitable.</td></tr>
<tr><td>#2

</td><td>While both trailers are running, Trailer 1 does not have the CHP or pasteurizer
Macerator & screw press
Chiller unit & dryer
Odor scrubber tower
Microfiltration & ultrafiltration
Reverse Osmosis
Selective Electrodialysis
UVOX</td><td>AD sites which have on-site pasteurization and available power. The AD site will likely have some storage space for digestate, and hence a mobile solution to occasionally service the site is suitable.</td></tr>
<tr><td>#3

</td><td>Similar to Scenario 2, but the equipment is now skid-mounted as a semipermanent solution for AD sites.
Macerator & screw press
Chiller unit & dryer
Odor scrubber tower
Microfiltration & ultrafiltration
Reverse Osmosis
Selective Electrodialysis
UVOX</td><td>AD sites which have on-site pasteurization and an available power source. The site may not have adequate storage space for digestate and hence requires a semipermanent installation.</td></tr>
</table>

3. Results and discussion

3.1. Results from experimental campaigns

3.1.1. Digestate characterization

As expected, the digestate from different sources varied in nutrient and solids content, which highly depended on the characteristics of the digester's feed. The total solids ranged from 10.6 to 61.4 g/L, with the digestate originating from WWTP sludge presenting the lowest value and the digestate from agricultural waste the highest value, while mixed waste and pig manure digestate solids were 17.95 and 16.8 g/L, respectively (Figure 2(a)). High solids concentrations are attributed to the low biodegradability of lignocellulosic materials derived from agricultural wastes, while low solids concentrations are due to the high biodegradability of organic wastes. Figure 2(b) shows the concentrations of the main nutrients, i.e., ammonium, phosphates, and potassium (K) in the digestates. The values of solids and nutrients are in general agreement with the literature [25], [26], [27]. Agricultural waste digestate showed the highest concentrations of all three nutrients, while the lowest nutrient concentrations were observed in WWTP sludge digestate [26]. The largest variation in terms of concentration was observed for K ions, which ranged from 193 to 5085 mg/L, with ammonium varying in about half that range (876-3059 mg/L) and phosphates nearly an order of magnitude lower (28-754 mg/L).

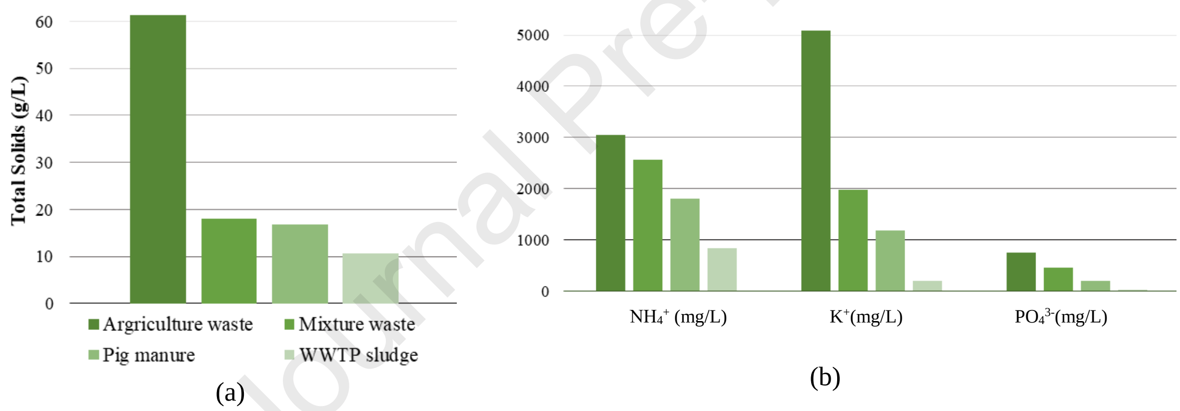


Figure 2. Concentrations of (a) solids and (b) nutrients of the various digestates.

3.1.2. Solids removal

The concentrations of the total solids in the liquid fraction after various membrane processes are illustrated in Figure 3. It can be seen that there is a progressive increase in solids removal as the processed materials pass through finer membranes in all cases. For WWTP sludge digestate, MF was not necessary because the plant used centrifugation with the addition of coagulants, leading to low solids content; therefore, UF was applied directly to the centrifuged liquid stream. During MF treatment, total solids removal varied from 41% to 57%, while during UF treatment, the removal percentages ranged from 5% to 90%, with the highest removal achieved in the case of agricultural digestate and the lowest in the case of WWTP sludge digestate. These values are in general agreement with those reported in the literature for the filtration of manure and mixed waste digestate [28], [29]. The RO permeate recovered at the end of each digestate processing run is entirely free of suspended and almost free of dissolved solids.

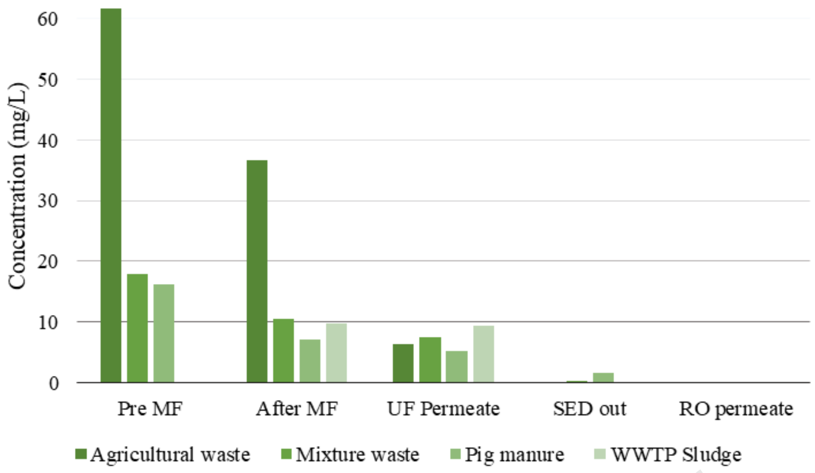


Figure 3. Solids concentrations after each process step.

3.1.3. Nutrients fate

Figure 4 depicts the concentrations of the three main nutrients after each membrane process, ammonium (Figure 4a), K (Figure 4b) and phosphates (Figure 4c). As the liquid feed passes through the filtration units, the nutrients are divided between the permeate stream and the concentrate of each unit. Ammonium and K are barely retained by MF and UF, with retention rates ranging from 2% to 14%. In UF, the rejection is slightly higher for all ions because the membrane is finer, leading to a larger mass/volume of UF concentrate compared to MF concentrate. However, phosphate rejection is much higher, with only 10% to 15% of the phosphates in the digestate making it to the UF permeate. This most likely occurs because phosphates tend to adhere to the finer solids rejected by the UF [26], while ammonium and K do not.

As described earlier, a selective electrodialysis unit was employed for the recovery of nutrients from the filtered digestate. This unit features a tank for the feed and three additional tanks that receive the separated ions, referred to as the product tanks. At the end of the experiment, 95% or more of the K and ammonium had migrated to the monovalent product tank, 6-42% of the phosphates to the anionic product tank, and 85-95% of the calcium and magnesium (not shown) to the cationic product tank. The low recovery of phosphates can be partly attributed to their large ionic radius and consequent low mobility [30], as well as to membrane fouling, which is more extensive on AEMs than on CEMs [31], [32] This leaves the digestate largely free of ions (SED out in Figure 4), facilitating greater water recovery in the subsequent RO. The highest recoveries of all three nutrients were achieved with WWTP sludge digestate, while the lowest recoveries were observed with the mixed waste digestate.

Finally, the RO unit was fed with ion-depleted digestate, which facilitates high rejection values. For all three of these ions, the rejection was above 85%, reaching nearly 100% for phosphate ions, comparable to values in the literature [12]. On the other hand, the RO concentrate comprises a small volume with a relatively low ionic load and a higher organic load (see Table 4 and discussion in 0).

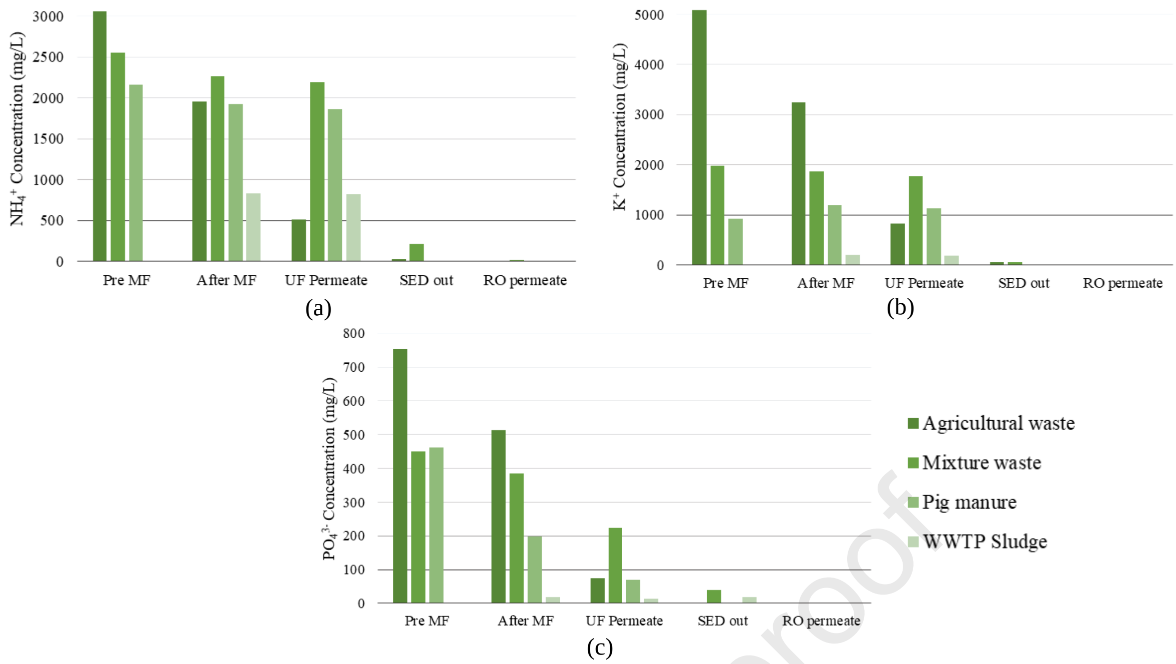


Figure 4: Nutrients concentrations after each process treatment: (a) Ammonium, (b) Potassium and, (c) Phosphates.

3.1.4. Potential products

3.1.4.1. Fertilizers production

In contrast to other membrane processes, SED has the main advantage of concentrating and selectively separating nutrients into different product solutions. This allows for the mixing of products, such as cationic and anionic to create valuable products like fertilizers [30]. SED achieves high ammonium recovery, yielding a brine product rich in nitrogen. However, the direct application of this product as a fertilizer is not feasible due to the high NaCl concentration (>10 g/L). Therefore, nitrogen must be further recovered, for example, by ammonia stripping to produce $(NH_4)_2SO_4$ fertilizer [15]. The brine product also contains a high concentration of K (up to 5721.8 mg/L). However, recovering potassium as a fertilizer salt could be quite challenging. Mixing anionic (phosphate-rich), cationic (magnesium-rich), and ammonia-stripped brine (potassium-rich) separated streams could result in the production of $KMgPO_4{\cdot}6H_2O$ (MPP), a slow-release fertilizer [33]. Phosphorus could be recovered via (selective) precipitation from the anionic product or a mixture of the anionic and one or both of the cationic and brine products as NH_4MgPO_4, $KMgPO_4$, $Ca_3(PO_4)_2$, $Mg_3(PO_4)_2$, $NH_4H_2PO_4$, or $(NH_4)_2HPO_4$ salts [30].

In the present study, the concentrations of magnesium and phosphates in the respective products are insufficient for struvite precipitation. To adjust the Mg/PO_4 ratio, it is essential to add $MgCl_2$ appropriately. The experimental procedure for struvite precipitation was described in the authors' previous communications [34]. The achieved phosphorus recovery was approximately 75%; however, the reclaimed solid was highly contaminated with other salts, predominantly calcium carbonate. Future efforts will focus on carbon dioxide removal through CO_2 stripping prior to precipitation to enhance struvite recovery [35], [36].

Another salt recovered from SED products is $(NH_4)_2SO_4$, obtained through lab-scale ammonia stripping as described in Section 0. In all cases, 91.9% to 99.8% of ammonium could be recovered.

3.1.4.2. Water recovery

In this study, the digestates consisted of approximately 94-99% water, and up to 58% of it was reclaimed at the end of the overall treatment process as RO permeate. This value is much higher than that reported by Adam et al. [37], who employed nanofiltration before their RO, indicating that the combination of SED with RO is most preferable in terms of volume reduction and water reclamation. The produced water was found to be of good quality [38], without color or odor and almost completely deionized in all cases. Table 4 presents the characteristics and volumes of produced water for all studied cases.

Table 4. Water and concentrates volume and characteristics.

	Volume (%)⁺	**TS (g/L)**	**NH_4^+ (mg/L)**	**K^+ (mg/L)**	**PO_4^{3-} (mg/L)**
			UF concentrate		
Manure case	33	9.00	1941.5	1214.8	133.1
Mixed waste case	22.5	14.35	1967.7	1716.9	465.6
Agri-waste case	44.2	19.76	1342.8	2221.5	268.9
WWTP sludge case	35	9.56	811.7	186.0	28.4
			RO concentrate		
Manure case	6	4.66	78	116.5	44.1
Mixed waste case	11	6.25	320.75	243.6	295.4
Agri-waste case	8	10.69	83.6	154.65	ND*
WWTP sludge case	7	2.96	ND*	10.41	79.0
			Water recovered		
Manure case	50	0.00	0.6	0.6	ND*
Mixed waste case	56	0.01	15.5	3	0.6
Agri-waste case	48	0.01	0.9	1.6	ND*
WWTP sludge case	58	0.01	ND*	0.3	0.15

⁺ % of received digestate volume.

* ND: Not detected

3.1.4.3. Concentrates

Concentrates were produced during the treatment of digestate with various pressure-driven membrane processes. The UF concentrate constitutes only 22.5-35% of the initial digestate volume treated. This nutrient-rich fraction contains approximately 35% of the digestate's available ammonium and potassium content and 24-56% of the corresponding phosphorus. The RO concentrate makes up only 6-11% of the initial digestate volume treated and contains little ammonium and potassium (Table 4) as most of these are retrieved in the SED. On the contrary, the phosphorus content was considerable, reaching just over 60% of the initial phosphates in the case of WWTP digestate. The high concentration of phosphorus in the RO concentrate, combined with the low contaminant levels relative to the UF concentrate, makes it an attractive product stream of the overall process. Both fractions could be further treated for potential nutrient retrieval, returned to the digester (since they also have a high organic carbon load), or even used directly as fertilizers if their contaminant levels do not exceed regulatory limits [17].

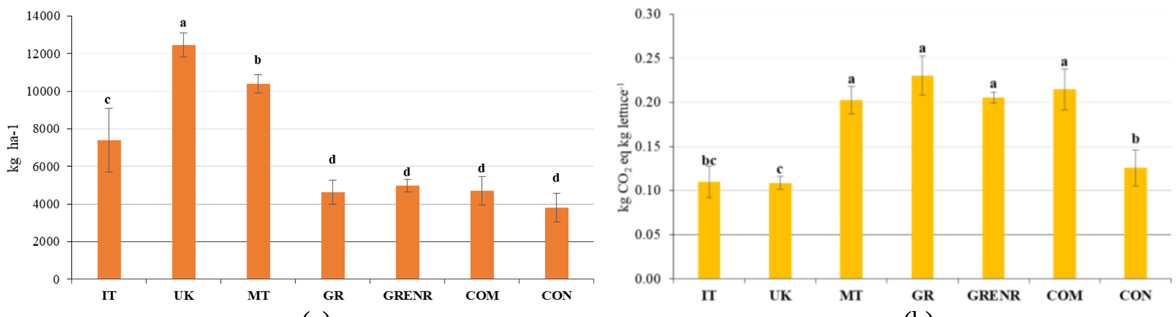
3.2. Antibiotics removal

The use of UVOX Redox® technology, which is based on UV/O_3 oxidation, was combined with digestate nutrient recovery in various configurations. The order in which these technologies are applied significantly influences the efficiency of antibiotic removal. Specifically, when the UF permeate was treated before the SED module, pharmaceuticals were removed by 90% in 2 hours under UVOX treatment and in 1 hour with the addition of H_2O_2. The efficacy of the UVOX treatment decreased, taking nearly twice as long to achieve the same level of pharmaceutical removal when UVOX treatment was applied after the SED unit. This can be attributed to the presence and catalytic effect of certain metal ions, such as Fe^{2+} and Co^{2+}, in the digestate, which promote the formation of OH· radicals from O_3. Consequently, the overall efficiency is enhanced when UVOX treatment is used before the SED. Conversely, the efficacy decreases when UVOX treatment is applied after the SED due to the absence of these catalytic metal ions, as they are removed from the liquid phase during the SED process [24], [39]–[42]. Additionally, UV transmission could serve as a process monitoring parameter since it shows a high correlation with both DOC and pharmaceutical removal, as demonstrated by Moradi et al. [24].

3.1. Crop growth test

In the field trials, the highest crop yields were observed with UK, MT, and IT fertilizers (12,458, 10,382, and 7,375 kg ha^{-1}, respectively) due to the higher total N and ammonium-N content that was more efficiently available to the plants (Table 2). This observation is supported by the fact that yields with GR, GRENR, and COM fertilizers were similar to CON (4,632, 4,966, 4,706, and 3,809 kg ha^{-1}, respectively) (Figure 5). In all of these treatments, the amount of total N and ammonium-N were lower (or 0 in CON) compared to the first three treatments. This resulted in a production gap between the two treatment blocks, favouring MT, UK, and IT over GR, GRENR, COM and CON. The number of leaves did not significantly differ between treatments, but plant diameter and height (Figure S1 & S2), like the yields, were higher with UK, MT, and IT, suggesting more efficient N uptake under these treatments. These observations were further supported by chlorophyll content analysis and NDVI, with the highest results observed for UK and MT, but not IT (Figure S3 & S4).

Greenhouse gas flux results are reported in the Supplementary Material. Cumulative carbon dioxide (CO_2) emissions during the growing season were higher with UK, GR, GRENR, and COM fertilizers (average of 986 kg C ha^{-1}). MT and IT showed lower CO_2 emissions (average of 819 kg C ha^{-1}), though these were still higher than those from CON (464 kg C ha^{-1}), suggesting an increase in microbial community activity due to fertilization. In terms of methane emissions, the MT treatment resulted in a small CH_4 consumption (-0.1 kg C ha^{-1}), while all other treatments emitted at least 0.02 kg C ha^{-1} (Table S1). This is likely due to the source of the fertilizer (processed digestate from municipal wastewater) having a presumably lower presence of methanogenic bacteria. Nitrous oxide emissions from MT-treated pot trials were significantly higher than those from other treatments (4.14 kg N ha^{-1}), probably due to the high total N and ammonium contents. Regarding cumulative impacts, MT and UK had the highest Global Warming Potential (GWP), while IT had lower values, comparable to CON (Figure 5). Analysis of yield-scaled emissions showed that UK and IT maintained high yields while reducing environmental impacts.



(a) (b)

Figure 5. Crop yields expressed as kg of lettuce (fresh weight) per hectare (a) and yield-scaled emissions expressed as $kgCO_2eq$/kg of lettuce (fresh weight) (b) for IT (solid fraction of digested crop wastes from Latina, Italy), UK (solid fraction of digested food wastes from Warminster, United Kingdom), MT (digested municipal wastewaters from Xghajra, Malta), GR (digested pig manure from Kozani, Western Macedonia - Greece), GRENR (digested pig manure mixed with the phosphorus (P)-enriched ultrafiltration concentrate from Kozani, Western Macedonia - Greece), COM (commercial organic fertilizer, Actiplus, Fertileva), CON (control pots without fertilization).

3.2. Business model results

CAPEX and OPEX for the three NOMAD operational scenarios are presented in Table 5, accounting for the inclusion and exclusion of nutrient recovery and pharmaceutical destruction unit functions (SED & UVOX) for each scenario. Similarly, CAPEX and OPEX data has been provided for both single shift operation (50 t/d) and double shift operation (100 t/d).

Table 5. Comparison of CAPEX and OPEX across all three scenarios.

		With SED & UVOX		**Without SED & UVOX**	
		50 t/d	100 t/d	50 t/d	100 t/d
Scenario 1	CAPEX (€)	1180433	1231573	1032666	1102868
	OPEX(€/year)	364093	716956	357124	708182
Scenario 2	CAPEX (€)	597842	619904	458489	491242
	OPEX(€/year)	152029	297528	142975	283214
Scenario 3	CAPEX (€)	580289	580129	430411	454961
	OPEX(€/year)	114068	222043	108654	213041

As detailed in Table 5, the CAPEX and OPEX for Scenario 1 are significantly higher than those for Scenarios 2 and 3. This is primarily due to the high CAPEX associated with the inclusion of a CHP unit, which generates power for operating the trailer components when electricity is not available, and the fuel-related OPEX costs for engine operation and power supply to downstream unit functions. In contrast, Scenarios 2 and 3, which do not include a CHP unit, assume that power will be procured from the grid at a lower unit cost than what is achievable via the CHP unit. The comparison between single-shift and double-shift operations across all scenarios estimates that while OPEX is likely to double, CAPEX would remain unchanged.

The modeling results indicate that the skid-mounted Scenario 3 is the most commercially attractive option for a single user, with an IRR of 50.6% after 5 years and a 1.71-year payback period. This is likely due to its lower CAPEX and maintenance costs compared to mobile Scenarios 1 and 2. However, since Scenarios 1 and 2 are designed to be shared among multiple smaller plants, Scenario 2 may also be competitive, depending on the number of plants participating in the network. Scenario 2 has an IRR of 41.6% after 5 years and a very reasonable 1.96-year payback period. Indeed, Scenario 1 could be promising in a different context where micro/small AD plants operate without on-site pasteurization, relying on the NOMAD technology to meet this need. This could save significant CAPEX and OPEX costs across a local network.

Various routes to market, including a range of ownership models, were considered during this study, along with revenue streams and potential cost-saving opportunities for customers. Table 6 presents a summary of the exploitation pathways evaluated, along with the proposed service offering(s). For the purposes of this study, carbon credits were excluded as an additional source of revenue due to the complexity and costs associated with proving the displacement of emissions resulting from the NOMAD technology operation.

Table 6. Routes to Market, revenues and cost saving opportunities.

Route to market	Description	Revenue streams and cost saving opportunities
Owning and operating the NOMAD units	The NOMAD team owns and operates the equipment and services client AD sites	• Gate fees for digestate treatment • Sale of fibre/compost • Sale of fertiliser products • Sale of recovered water
Sale/lease equipment	The NOMAD team sells/leases the equipment to client AD sites	• Sale/ lease revenue New revenue streams and cost savings are also enabled for the client AD site, such as: • Reduced digestate management, storage & disposal costs • Sale of fibre/compost or offset of fibre/compost purchase • Offset of water demand via reuse of recovered water
Technology licensing	The NOMAD team licenses the technology	• Licensing revenue New revenue streams and cost savings for licensee as listed above are also generated

Under the "own and operate" model, the intention is for the technology developers to establish an operating company that would use the NOMAD technology to offer digestate management services to biogas operators. Revenue streams under this model would come from a digestate management service charge and the sale of generated fertilizers and process water. In contrast, under the "sale/leasing" model, the NOMAD technology would either be sold or leased to biogas operators, with operator training provided by the sales/leasing business. This model would create a product supply revenue stream for the sales/leasing business while allowing biogas operators to benefit from the cost savings and revenue streams realized by NOMAD. For customers, the NOMAD leasing model offers a clear opportunity to capitalize on the benefits of NOMAD without the high purchase costs. Finally, licensing the technology to a third party would provide a stream for the inventors and allow the licensee to exploit the NOMAD technology as they see fit.

4. Conclusions

In conclusion, the proposed technology is highly effective in treating diverse digestates and producing valuable products. It combines microfiltration, ultrafiltration, and reverse osmosis to reduce solids and generate clean water, accounting for 48% to 58% of the initial digestate. The ultrafiltration concentrate, retains 40-60% of the phosphates, while UF permeate can be processed into alternative fertilizers like struvite and ammonium sulfate through selective electrodialysis. Additionally, pharmaceuticals are efficiently removed using UV/O_3 oxidation, especially when performed before nutrient retrieval.

Crop growth tests indicate that digestates from agricultural waste, food waste, and WWTP sludge enhance plant growth more than commercial fertilizers, with agricultural and food waste digestates resulting in the lowest greenhouse gas emissions (~0.11 kg CO_2/kg lettuce). In terms of business viability, the skid-mounted system without CHP offers the best financial performance, with a 1.71-year payback period and a 50.6% IRR. The trailer-mounted option without CHP is also favorable, whereas adding CHP significantly increases the payback period and reduces IRR.

Overall, this technology provides both environmental and economic benefits. Its efficiency and product quality are notably affected by the type of digestate, including its nutrient and solids content, as well as its source, which influences the presence of pollutants such as pharmaceuticals.

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Highlights of Mobile solution for digestate transformation to high added-value products

- Mobile process for digestate refining and volume reduction
- NOMAD technology reclaimed up to 58% of water from digestate
- Achieved over 90% antibiotic removal within two hours using UVOX technology
- Produced fertilizers were at least as effective as commercial organic ones
- Five-year 41.6% return on investment and 1.96 payback period calculated

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: