Acta Agriculturae Scandinavica, Section B — Soil & Plant Science

ISSN: 0906-4710 (Print) 1651-1913 (Online) Journal homepage: www.tandfonline.com/journals/sagb20

Sustainability of bread from ancient wheat: environmental impact and economic assessment in organic and conventional supply chains

L. Verdi, F. Gerini, L. Azzini, G. Piracci, L. Casini & S. Orlandini

To cite this article: L. Verdi, F. Gerini, L. Azzini, G. Piracci, L. Casini & S. Orlandini (2025) Sustainability of bread from ancient wheat: environmental impact and economic assessment in organic and conventional supply chains, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 75:1, 2590238, DOI: 10.1080/09064710.2025.2590238

To link to this article: https://doi.org/10.1080/09064710.2025.2590238

Published online: 22 Nov 2025.

ACTA AGRICULTURAE SCANDINAVICA, SECTION B — SOIL & PLANT SCIENCE
2025, VOL. 75, NO. 1, 2590238
https://doi.org/10.1080/09064710.2025.2590238

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Sustainability of bread from ancient wheat: environmental impact and economic assessment in organic and conventional supply chains

L. Verdi[a], F. Gerini[a], L. Azzini[a], G. Piracci[b], L. Casini[a] and S. Orlandini[a]

[a]Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Firenze, Italy; [b]Department of Land, Environment, Agriculture and Forestry (TeSAF), Università degli Studi di Padova, Legnaro (PD), Italy

ABSTRACT

This study assesses the environmental and economic sustainability of bread production chain using an ancient soft wheat (var. Verna), cultivated under conventional and organic farming systems. A Life Cycle Assessment from wheat cultivation through baking to bread production was conducted using the CML 2001 method, alongside an economic analysis covering production, milling, and baking stages. Results revealed that the organic system, despite yielding 45% less grain than conventional (1,524 vs. 2,815 kg ha^{-1}), exhibited lower environmental impacts in key categories per kg of bread: global warming (0.95 vs. 1.47 kg CO_2eq), freshwater ecotoxicity (0.02 vs. 0.06 kg 1,4-DBeq), and eutrophication (0.01E-1 vs. 0.04E-1 kg PO_4eq). The processing phase – particularly baking – accounted for the largest share of impacts across both farming systems (>70% of greenhouse gas emissions). Economically, organic bread production costs were 11% higher (5.00–5.20 € kg^{-1} vs. 4.40–4.60 € kg^{-1}), with the milling stage showing a > 100% cost increase in organic due to smaller scale and certification requirements. Despite modest profit margins, especially at the farm level, European Union subsidies contribute to maintaining the viability of the organic model. Findings highlight the importance of energy-efficient processing and targeted agronomic strategies to enhance the sustainability of traditional cereal-based food systems.

ARTICLE HISTORY
Received 8 August 2025
Accepted 11 November 2025

KEYWORDS
Agri-food value chain; global warming; LCA; production costs; Triticum aestivum

Introduction

Wheat is one of the most widely cultivated cereals worldwide, forming a key part of the diet of a significant portion of the global population (Erenstein et al. 2022). Despite its pivotal role in food production to support global population growth, the intensive use of synthetic inputs – such as fertilisers, pesticides, and herbicides – essential for maintaining high yields, has serious environmental impacts. For this reason, the Farm to Fork Strategy, within the European Green Deal, highlights the relevance of reducing the use of external inputs in agriculture, aiming to cut fertilisers use by 20% and reduce nutrients losses and chemical pesticides use by 50% by 2030 (EC 2020). This approach is also promoting the expansion of organic farming as a strategy to mitigate the environmental impact of the agricultural sector.

Organic farming of wheat generally shows lower environmental impacts compared to conventional farming, despite potentially lower yields (Mukosha et al. 2023). Although organic farming requires more machinery than conventional agriculture, it remains the more environmentally sustainable option, reducing pollution, biodiversity loss, soil erosion, and energy consumption while improving soil and water quality (Tuomisto et al. 2012; Holka and Kowalska 2025; Sanders et al. 2025). Recently, consumers attention has increasingly shifted toward healthy, locally sourced, and fresh food, accompanied by a rising concern for the sustainability of the food supply chain resulting in the increased growth of organic goods market (Chiriacò et al. 2017). However, lower yield per hectare, approximately between 20 and 35% than conventional systems, necessitates a larger land area to meet food demand, posing a significant challenge about organic farming (Seufert et al. 2012). In this sense, an 11-year study conducted in Italy reported that organic farming resulted in lower grain yields and greater soil nitrogen depletion compared to conventional systems,

CONTACT F. Gerini francesca.gerini@unifi.it Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Piazzale delle Cascine 18, Firenze 50144, Italy

confirming that organic farming requires more land to achieve yields similar to those of conventional systems, which may result in additional environmental impacts (Benincasa et al. 2016). The environmental impacts of organic durum wheat production were also evaluated in a recent study conducted in Southern Italy, which reported that organic farming reduces the use of synthetic chemicals and plastic waste by up to 100%, decreases diesel consumption by 15%, and prevents soil and groundwater pollution. However, due to lower yields, it generates a lower gross income compared to conventional production (Bux et al. 2022). Nonetheless, higher market prices and lower input costs can partially or even fully compensate for these yield-related economic disadvantages. di Cristofaro et al. (2024), in a comprehensive study on durum wheat in Central Italy that applied the Life Cycle Assessment (LCA) approach, highlighted that conventional farming ensures lower environmental impacts compared to the organic system. This outcome is mainly attributed to the higher yields achieved under conventional management. However, the economic analysis of the supply chain revealed that the organic system results in the lowest impacts per income unit, reflecting consumers' appreciation for sustainable and heritage wheat varieties. Further improvements in the environmental performance of organic farming could be achieved by increasing crop yields and optimising sowing and harvesting practices. In recent years, researchers have conducted extensive efforts to evaluate the actual environmental impacts of both organic and conventional farming systems on different foods (Tuomisto et al. 2012; Mukosha et al. 2023; Sanders et al. 2025).

Bread, being an essential part of the human diet, has been the subject of several assessments aimed at evaluating the environmental impacts associated with its production chain in both organic and conventional farming systems. While organic bread is generally preferred by consumers, especially when coupled with health information, its environmental footprint remains significant and under debate (Annett et al. 2008). A study on wholemeal bread in Italy reported that the organic production system had a 24% higher impact (1.55 kg CO_2eq kg bread^{-1}) compared to the conventional system (1.18 kg CO_2eq kg bread^{-1}), primarily due to the lower yields in organic system (Chiriacò et al. 2017). In contrast, a study from Spain reported lower environmental impact associated to organic bread production compared to conventional systems, due to the reduced use of fertilisers, which substantially lowers the environmental footprint of the cultivation phase (Camara-Salim et al. 2020). In line with the previous study, Goucher et al. (2017) observed that the cultivation of wheat accounts for over half of the environmental impact in bread production, with fertiliser use being the main contributor. A Norwegian study found that producing 1 kg of bread results in 0.95 kg CO_2-equivalent emissions, with on-farm processes responsible for about 50% of the impact (Korsaeth et al. 2012).

However, post-farm stages also play a crucial role in the overall environmental impact (Svanes et al. 2018). In particular, raw material and energy consumption are two key factors influencing the sustainability of the bread production chain (Camara-Salim et al. 2020). Chiriacò et al. (2017) observed that the bakery phase accounts for approximately 25% of the total environmental impact of the bread production chain, followed by the retail phase, which contributes an average of 15% to the total impact. In general, the most effective strategies to reduce the impact from the bread supply chain include: (i) improving farm management practices; (ii) minimising the fertiliser use; (iii) adopting packaging solutions that extend bread freshness and reduce waste (Korsaeth et al. 2012; Goucher et al. 2017; Svanes et al. 2018).

In addition to environmental considerations, the economic sustainability of the entire supply chain is a crucial factor in establishing a sustainable production system (Malorgio and Marangon 2021). Although organic goods can achieve higher market prices, they are also associated with higher production costs, including certified inputs, increased machinery use, and certification fees (Bellassen et al. 2022; Yu et al. 2022). In the wheat-to-bread chain, value is progressively added up to the baking stage, especially when wheats of ancient varieties or grains with certified quality or origin are processed through local mills and artisanal bakeries (Sacchi et al. 2019). These practices can strengthen the product's identity and improve market appreciation along the chain, although not always to the benefit of the agricultural stage, but rather of the downstream segments (Brunori et al. 2016).

The aim of this study was the assessment of the environmental impacts and economic sustainability of the production chain of an ancient wheat bread (Verna) under both organic and conventional farming systems. The LCA methodology from the cultivation to bakery phase was applied to quantify the environmental footprint, while an economic analysis examines cost structures and market dynamics. The findings provide insights into the trade-offs between environmental benefits and economic feasibility in sustainable bread production.

Materials and methods

Goal and scope definition

This study focused on assessing the environmental impacts and the economic sustainability of the bread production chain using an ancient variety of soft wheat (var. Verna), cultivated under both conventional (CONV) and organic (ORG) farming systems. The analysis allowed for the identification and characterisation of the critical stages within the production chain associated with the highest environmental burdens. This type of information provides essential insights for the critical evaluation of supply chain organisation and supports the development of strategies aimed at improving the sustainability performance of such systems.

Functional unit and system boundaries

The functional unit (FU) serves as the reference against which the impacts of the systems under study are calculated. Given that agriculture is a multifunctional sector and considering that this study encompasses both the cultivation of wheat and the processing of grain and flour for bread production, two distinct FU were employed for the respective stages (Nemecek et al. 2011). Specifically, the cultivation phase was assessed using 1 kg of wheat grain as the FU, while the processing phase was based on 1 kg of flour. In contrast, total impacts were calculated using a FU corresponding to 1 kg of bread. This approach was adopted to ensure that the FU were closely aligned with the respective phases of the supply chain. It also allowed for the comparison of results across different stages and for the weighted aggregation of impacts, yielding overall results expressed per 1 kg of Verna bread. The entire supply chain, from cultivation to processing, was based on the Pane Toscano PDO (Protected Designation of Origin) production specification and complied with the guidelines set forth in the regulatory document (Italian Official Gazette 2023). Verna wheat, like other ancient wheat varieties, is gaining increasing attention due to its specific traits, such as enhanced nutritional properties and its hardiness, which allows it to better compete with weeds, tolerate drought conditions, and require fewer inputs compared to modern cultivars (Venturi et al. 2021). Data for the cultivation phase were collected from 10 farms – 5 conventional and 5 organic – located in the Tuscany region, covering five growing seasons (2014/2015–2018/2019). Further details on system boundaries of cultivation phase, geographic distribution of the farms, climatic characteristics of the area, and specific features of the Verna wheat production cycle in Tuscany are provided in Verdi et al. (2022). Differently, the processing phase was based on data from 2 mills and 2 bakeries, maintaining the comparison between conventional and organic systems. The selection of the facilities was made to ensure consistency with the origin of the wheat grain; therefore, mills and bakeries located in the provinces of Siena and Arezzo were chosen. The system boundaries for this phase included all milling and bakery activities, specifically: (i) transportation of grains from farms to milling facilities and of flour from mills to bakeries; (ii) energy and water consumptions; (iii) the complete life cycle of packaging materials used for processing inputs.

Impact assessment

In the present study, the GaBi software, updated to version 10.9.0.31. was used to assess the environmental impacts of the Verna bread production chain. The impact assessment was conducted using the CML 2001 methodology updated to 2016 (Sphera Solution, Inc., Chicago, IL, USA), evaluating the following impact categories: global warming, freshwater ecotoxicity, seawater ecotoxicity, acidification, eutrophication, terrestrial ecotoxicity, human toxicity, ozone layer depletion potential, and photochemical ozone creation potential. These impact categories were selected as they are the most relevant for analyzing the sustainability and environmental impacts of agricultural systems (Table 1).

Life cycle inventory

Data collection for the Life Cycle Inventory (LCI) was conducted using specific checklists developed ad hoc for the cultivation and processing phases. Checklists were developed to cover all stages of the production process, from field cultivation to processing and bread production (Table 2). They were designed to

Table 1. Environmental impact categories, units and reference methods.

Impact categories	Abbreviations	Reference factors	Units	Reference methods
Global Warming	GW	Carbon Dioxide	kg CO2eq	CML2001 – Aug. 2016
Freshwater Ecotoxicity	FE	1,4-Dichlorobenzene	kg 1,4-Dbeq	″
Seawater Ecooxicity	SE	1,4-Dichlorobenzene	kg 1,4-Dbeq	″
Acidification	AC	Sulphur Dioxide	kg SO2eq	″
Eutrophication	EU	Phosphates	kg PO4-	″
Terrestrial Ecotoxicity	TE	1,4-Dichlorobenzene	kg 1,4-Dbeq	″
Human Toxicity	HT	1,4-Dichlorobenzene	kg 1,4-Dbeq	″
Ozone Layer Depletion Potential	OLDP	Chlorofluorocarbon-11	kg CFC-11eq	″
Photochemical Ozone Creation Potential	POCP	Ethylene	kg C2H4 eq	″

account for all material and energy flows involved in the bread production chain. Data were collected directly through structured interviews with farmers and bread producers along the entire supply chain. The inventories correspond to the two production chains, each with its distinct phases, resource consumption, and yields (Figure 1). Primary data from the inventories were analyzed using the Ecoinvent v.3.3 and the GaBi databases, with processes modelled based on geographical and technological analogies. The inventory analysis encompassed all utilised resources and environmental emissions associated with wheat cultivation and processing, from seed production for sowing through to harvest, transportation to milling plants, milling resource consumption and emissions, transportation to the bakery, and resource consumption and environmental emissions during baking.

Data from the cultivation phase revealed relevant variations in input use and agricultural management strategies between conventional (CON) and organic (ORG) systems, with the most significant differences observed among organic farms. Each farm followed consistent practices over the years, and to define a reference cultivation model, inputs were weighted based on their contribution across the five farms (Verdi et al. 2022). To identify the main emission drivers, the cultivation phase was divided into six distinct macro-categories: mechanical practices, fertiliser manufacturing, use of fertilisers, herbicide and fungicide production, ancillary materials, and waste materials. The study evaluated the environmental impacts associated with each category, considering inputs such as machinery use, fuel consumption, types of fertilisers, and packaging materials. With regard to the processing phase, impact assessment was conducted by analyzing the main stages involved in the transformation of wheat grain into flour and subsequently into bread. These stages primarily included transportation, milling, storage, baking, and packaging.

Life cycle impact assessment (LCIA)

The Life Cycle Impact Assessment (LCIA), conducted using GaBi v10.9.0.31, quantified the environmental impacts across various categories based on the data collected in the LCI. By combining inventory data with equivalency factors, characterisation factors were determined for each impact category (Table 3).

The impacts were expressed using specific indicators corresponding to each category. Subsequently, the LCIA results were normalised using reference values at the EU25 level (CML 2001, 2016 update), yielding

Table 2. List of the main inputs for the cultivation and processing phases for the conventional and organic farming systems.

Phase	Input	Unit	Conventional farming	Organic farming
Cultivation phase	Seeds	kg/ha	180.00	180.00
	Nitrogen fertilisers	kg N/ha	410.00	138.61
	Phosphorus fertilziers	kg P_2O_5/ha	220.00	116.00
	Seed tanning products	l/ha	166.70	200.00
	Fungicides	kg/ha	166.67	-
	Herbicides	l/ha	248.34	-
	Diesel	l/ha	139.30	104.26
	Wire for straw bales	kg/ha	2.00	2.00
Processing phase (mill)	Paper bags	kg for kg of flour	0.05E-2	0.03E-1
	Plastic bags	kg for kg of flour	0.25E-3	0.03E-1
	Energy consumptions	kW/h for kg of flour	0.92	6.81
Processing phase (bakery)	Paper bags	kg for kg of bread	0.05E-1	0.05E-1
	Ingredients for bread processing	kg for kg of bread	3.00	1.50
	Energy consumptions	kW/h for kg of bread	2.32	1.71

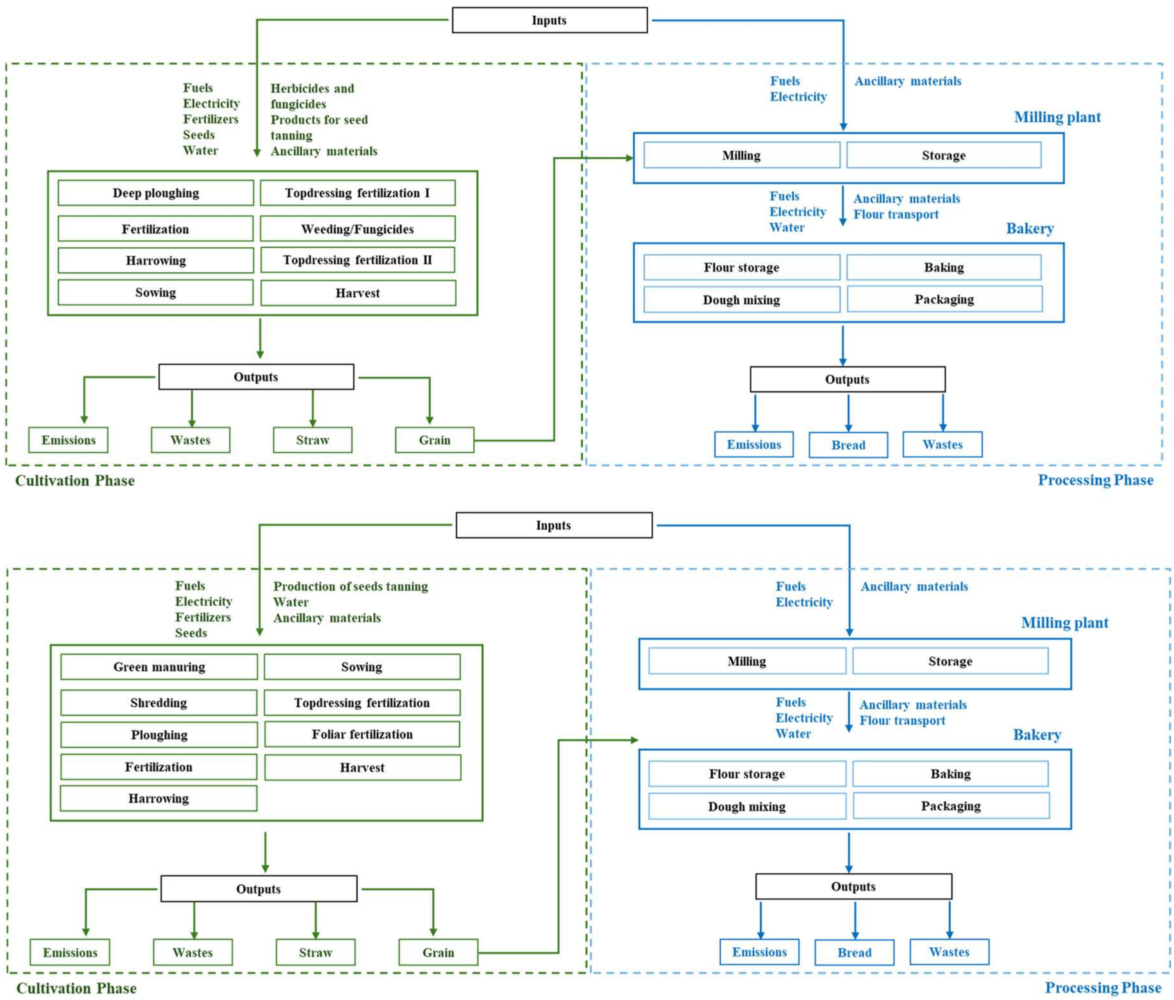

Figure 1. System boundaries of Verna conventional (a) and organic (b) production chain.

dimensionless values that enabled direct comparison across different impact categories (Table 4). This normalisation process facilitated an objective interpretation of the relative magnitude of each impact, by relating the indicator values per FU to the corresponding normalisation factors.

Table 3. Environmental impacts between conventional (CONV) and organic (ORG) Verna bread production chain from the cultivation and processing phases. Results are expressed as per one kg of bread for each impact category.

Impact category	Units		Cultivation phase	Processing phase	Total
GW	kg CO2eq	CONV	3.50E-01	1.12E + 00	1.47E + 00
		ORG	2.16E-01	7.35E-01	9.51E-01
FE	kg 1,4-Dbeq	CONV	3.12E-02	9.22E-03	4.04E-02
		ORG	1.09E-02	5.61E-03	1.65E-02
SE	kg 1,4-Dbeq	CONV	1.05E + 02	1.95E + 02	3.01E + 02
		ORG	3.91E + 01	7.34E + 01	1.12E + 02
AC	kg SO2eq	CONV	2.36E-03	3.12E-03	5.47E-03
		ORG	1.87E-03	1.95E-03	3.82E-03
EU	kg PO4-	CONV	3.25E-03	3.30E-04	3.58E-03
		ORG	9.80E-04	2.17E-04	1.20E-03
TE	kg 1,4-Dbeq	CONV	3.63E-04	1.57E-03	1.93E-03
		ORG	1.93E-04	5.07E-04	7.00E-04
HT	kg 1,4-Dbeq	CONV	6.61E-02	8.05E-02	1.47E-01
		ORG	2.18E-02	2.65E-02	4.83E-02
OLDP	kg CFC-11eq	CONV	3.27E-08	2.17E-09	3.49E-08
		ORG	3.74E-08	9.11E-10	3.84E-08
POCP	kg C2H4 eq	CONV	4.47E-05	1.86E-04	2.31E-04
		ORG	4.07E-05	8.75E-05	1.28E-04

GW = Global Warming; FE = Freshwater Ecotoxicity; SE = Seawater Ecotoxicity; AC = Acidification; EU = Eutrophication; TE = Terrestrial Ecotoxicity; HT = Human Toxicity; OLDP = Ozone Layer Depletion Potential; POF = Photochemical Ozone Creation Potential.

Table 4. Normalised environmental impact (Europe 25, CML v3.06, 2016) across considered impact categories.

Impact category	Units	Normalisation factors	CONV	ORG
GW	kg CO2eq	1.99E-13	2.92E-13	1.89E-13
FE	kg 1,4-Dbeq	1.93E-12	7.80E-14	3.18E-14
SE	kg 1,4-Dbeq	8.57E-15	2.58E-12	9.64E-13
AC	kg SO2eq	3.55E-11	1.94E-13	1.36E-13
EU	kg PO4-	7.58E-11	2.72E-13	9.07E-14
TE	kg 1,4-Dbeq	2.06E-11	3.98E-14	1.44E-14
HT	kg 1,4-Dbeq	1.29E-13	1.89E-14	6.23E-15
OLDP	kg CFC-11eq	1.12E-08	3.90E-16	4.30E-16
POCP	kg C2H4 eq	1.18E-10	2.72E-14	1.51E-14

GW = Global Warming; FE = Freshwater Ecotoxicity; SE = Seawater Ecotoxicity; AC = Acidification; EU = Eutrophication; TE = Terrestrial Ecotoxicity; HT = Human Toxicity; OLDP = Ozone Layer Depletion Potential; POF = Photochemical Ozone Creation Potential.

Economic sustainability assessment

Alongside the LCIA, a complementary production cost analysis was conducted to assess the economic sustainability of bread derived from *Triticum aestivum* var. *Verna* wheat, comparing CONV and ORG farming systems. This investigation aimed to quantify and contrast the cost structures across the supply chain, from primary production to final processing, thereby providing additional insights into the economic performance of each production chain.

The analysis was based on the same sample used for the environmental assessment. Specifically, data were collected from ten farms cultivating Verna wheat (five conventional and five organic), two milling facilities, and two bakeries, all located in the region of Tuscany. The farms were selected to ensure a balanced representation of the Verna wheat production systems in the region, considering farming method, geographical distribution, and continuity of cultivation over at least five consecutive years. This sampling strategy ensured both vertical integration along the supply chain and internal coherence between environmental and economic data. Data collection took place in 2023 and relied on structured questionnaires specifically developed for each stage of the supply chain: agriculture, milling, and baking. Interviews were administered in person by trained researchers following a preliminary selection of participants based on the abovementioned characteristics and willingness to participate.

Each questionnaire included a dedicated section for the collection of economic data, focusing on key input categories such as material costs, energy use, labour, and capital expenditures. For agricultural producers, cost items included seeds, fertilisers, pesticides purchases, and outsourced mechanical operations. For milling and baking enterprises, the survey captured expenditures related to transport, labour, infrastructure (both fixed and mobile), certification requirements, and raw material procurement. To ensure comparability between the CONV and ORG production systems, a set of simplifying assumptions was applied. All field operations were assumed to be fully outsourced, i.e. performed by third-party contractors, thereby excluding machinery depreciation, labour, and overhead costs directly borne by the farm (Consorzio Gian Pietro Ballatore 2007). Standard cost values for these outsourced services were retrieved from the regional official pricing list for agricultural operations published by the Regione Toscana (Prezzario Lavori 2025 Regione Toscana, Delibera Regionale n. 1406 of 25/11/2024). Moreover, farmland was assumed to be fully amortised, and thus no land rental costs or capital depreciation charges were included in the final computation of production costs.

All cost data were standardised to a per-kilogram basis and expressed in euros per kilogram of bread. For each stage of the supply chain, average costs were calculated separately for the organic and conventional systems, distinguishing between fixed and variable components.

Results

The environmental impacts of Verna bread were assessed adopting the from cradle-to-grave approach including the cultivation and processing (milling and baking) phases. This LCA analysis resulted in 9 impact categories; however, 5 of them represented the main part of the impacts (Table 4). In particular, Global Warming, Freshwater Ecotoxicity, Seawater Ecotoxicity, Acidification and Eutrophication represented the 97.72% and 97.56% of the total impacts of CONV and ORG systems, respectively. In general, the highest impacts were observed from the CONV system on all the considered impact categories despite the lower yields of wheat grains from ORG accounting for almost 45% of those obtained from the conventional one.

Global warming

The rise in Earth's surface temperature is primarily driven by greenhouse gas (GHG) emissions. In agriculture, the most significant GHG include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Emissions of GHG are measured in terms of their global warming potential (GWP) relative to CO_2. They are expressed as kilograms of CO_2 equivalents (kg CO_2 eq) over a 100-year timeframe, following IPCC guidelines (IPCC 2023). The impacts of GW were similar between the two systems accounting for 8.34% (1.47 kg CO_2eq) and 13.07% (0.95 kg CO_2eq) of the total impacts for CONV and ORG, respectively (Table 3). In both systems, the processing phase accounted for almost twice the environmental impacts compared to the cultivation phase (Figure 2).

Freshwater ecotoxicity

The presence of toxic substances generated by different anthropogenic processes can negatively affect freshwater ecosystems. This impact, categorised as freshwater ecotoxicity, is quantified in terms of kilograms of 1,4-dichlorobenzene equivalents (kg 1,4-DBeq). We observed higher impacts in CONV with 0.06 kg 1,4-DBeq compared to 0.02 kg 1,4-DBeq from ORG (Table 3). The contributions to total impacts were 2.23% and 2.20% for CONV and ORG, respectively. The cultivation phase accounted for the majority of environmental impacts in both production systems, contributing 77.21% in CONV and 66.00% in ORG (Figure 2).

Seawater ecotoxicity

This impact category relates to the emission of toxic substances into marine ecosystems and is expressed, similar to FE, in kg 1,4-DBeq. SE was the most impactful category in both systems, accounting for 73.65% and 66.59% of total impacts in CONV and ORG, respectively. The CONV system exhibited the highest impacts, with 300.74 kg 1,4-DBeq, compared to 112.46 kg 1,4-DBeq in ORG (Table 3). The contributions of the cultivation and processing phases were comparable between the two systems, with the processing phase generating the highest impacts, accounting for approximately 65% of the total (Figure 2).

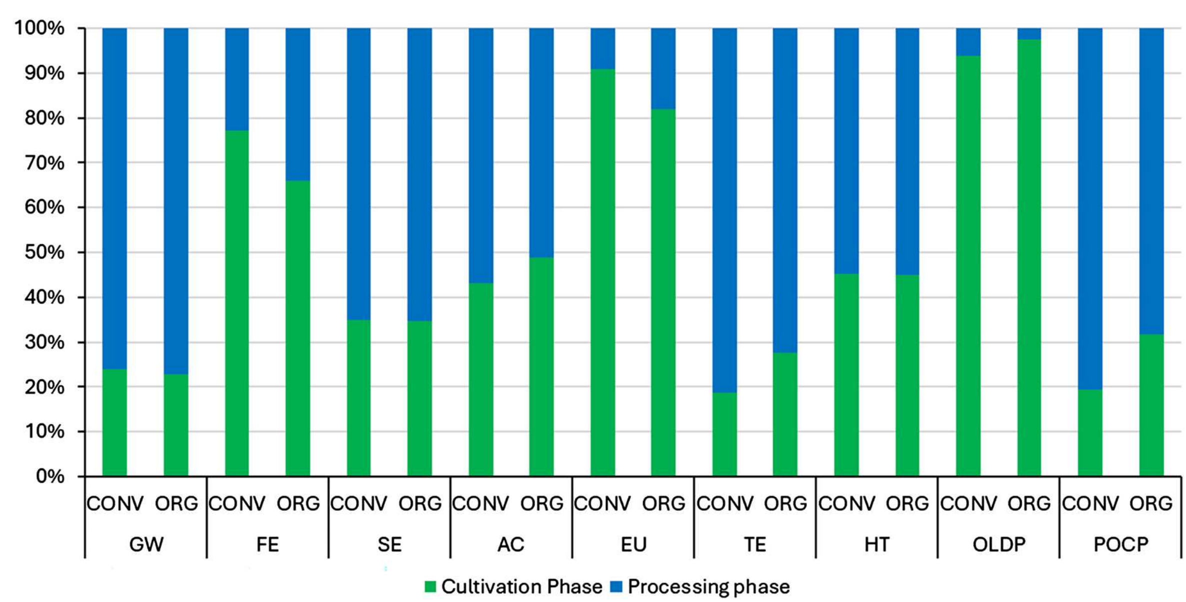

Figure 2. Relative contribution (percentage) of cultivation and processing phases to impact categories in Verna wheat bread production between conventional (CONV) and organic (ORG) systems. GW = Global Warming; FE = Freshwater Ecotoxicity; SE = Seawater Ecotoxicity; AC = Acidification; EU = Eutrophication; TE = Terrestrial Ecotoxicity; HT = Human Toxicity; OLDP = Ozone Layer Depletion Potential; POF = Photochemical Ozone Creation Potential.

Acidification

Acidification is an indicator that quantifies the release of protons into the environment. The effects of AC are typically expressed in terms of H^+ or, as in the present study, kg of sulphur dioxide equivalents (kg SO_2eq). The primary contributors to this indicator from anthropogenic processes include sulphur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3). Despite similar contributions to total impacts between the two systems (5.55% and 9.37% for CONV and ORG, respectively), CONV exhibited the higher impacts accounting for 5.47E-3 kg SO_2eq compared to the 3.82E-3 kg SO_2eq from ORG (Table 3). The contributions of the cultivation and processing phases are similar, although the latter has a greater impact, with CONV showing a higher contribution (56.95%) compared to ORG (51.04%) (Figure 2).

Eutrophication

Eutrophication is a degenerative process affecting aquatic ecosystems, driven by excessive inputs of fertilising substances such as nitrogen, phosphorus, and other stimulants compounds, which are transported to marine environments by rivers. Impacts of eutrophication are conventionally reported as kg of phosphates equivalents (kg PO_4^-eq). Eutrophication from the production process of cereals is primarily driven by agricultural activities, with key contributors including the leaching and erosion of nitrates and phosphates, NH_3 emissions resulting from excessive fertilisation, and NO_x released by tractor operations. Additionally, energy consumption during milling and baking processes plays a significant role in exacerbating eutrophication. The findings of this study indicate that the CONV system generated an environmental impact nearly three times greater than that of the ORG system (3.58E-3 kg PO_4^-eq and 1.20E-3 kg PO_4^-eq for CONV and ORG, respectively) (Table 3). In both production systems, the cultivation phase emerged as the most impactful, accounting for 90.79% and 81.89% of the total environmental burden, in CONV and ORG respectively (Figure 2).

Terrestrial ecotoxicity

Terrestrial ecotoxicity examines how toxic substances affect land-based organisms, including plants, soil microbes, insects, and larger wildlife. It assesses how pollutants impact biodiversity, soil health, and ecosystem stability, considering factors such as bioaccumulation, toxicity thresholds, and long-term environmental persistence, expressed as kg 1,4-DBeq. The CONV system had a greater contribution to this impact category than ORG, despite the relatively small contribution of TE to the total impacts (Table 3). In both systems, the processing phase showed the higher impact with 81.19% for CONV and 72.44% for ORG (Figure 2).

Human toxicity

The impact of toxic substances released into the environment on human health is referred to human toxicity category, encompassing both direct exposure through air, water, and soil, as well as indirect effects through the food chain and long-term bioaccumulation. Similarly to other ecotoxicity categories, HT is quantified as kg 1,4-DBeq. The higher impacts were observed from CONV (Table 3) and in both systems, the processing phase highlighted the higher impacts accounting to approximately 55% of the total (Figure 2).

Ozone layer depletion potential

The depletion of stratospheric ozone leads to higher exposure to ultraviolet rays, posing risks to living organisms. This impact category is quantified based on the emissions of ozone-depleting substances, such as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), measured in kilograms of CFC-11 equivalents (kg CFC-11eq). The impacts of OLDP were similar between the two systems (Table 3). The cultivation phase represented the principal factor of impacts in both CONV and ORG accounting for 93.79% and 97.63% of total impacts, respectively (Figure 2).

Photochemical Ozone Creation Potential

This indicator informs about the generation of tropospheric ozone, which results from the reactions of organic compounds under the influence of sunlight and high temperatures. Key contributors to this process include air pollutants like NOx, SO_2, and non-methane volatile organic compounds. These substances are predominantly released through fossil fuel extraction and distribution, vehicle emissions, and combustion activities. The impact is expressed in kilograms of ethene equivalents (kg C_2H_4eq). Similar contributions between CONV and ORG were observed (Table 3). The processing phase was the most impactful sector compared to the cultivation phase with a contribution of 80.64% and 68.26% for CONV and ORG, respectively (Figure 2).

Economic assessment

The economic analysis of the Verna wheat supply chain, conducted through a cost analysis per production stage (farm, mill, and bakery) and production method (CONV and ORG), highlights significant structural differences that impact the final production cost of the product. The total average costs, expressed in euros per kilogram of bread, are 4.40- 4.60 €/kg in the CONV and 5.00-5.20 €/kg in the ORG, with a differential of +11% in favour of the former.

This overall discrepancy results from a cumulative difference in unit costs at each stage of the supply chain. The values reported in Table 5, expressed in euros per kilogram, provide an overview of the composition and incidence of average costs in each step of the supply chain. At the agricultural stage, fixed costs were considered negligible in both production methods, as it was assumed that all field operations were carried out exclusively through contracted services (e.g., Verdi et al. 2022). At the agricultural stage, the cost per hectare amounts to 1,271.09 € in the CONV and 816.56 € in the ORG. However, due to the significant difference in average yields (2,815 kg ha^{-1} in CONV versus 1,524 kg ha^{-1} in org), the grain production cost per kilogram is 0.30-0.45 € kg^{-1} in CONV and 0.40-0.54 € kg^{-1}in ORG. In relative terms, despite the lower absolute cost per hectare in the ORG, the lower productivity results in a 19% increase in the unit cost per kilogram of grain produced.

At the primary processing stage (milling), fixed and variable costs amount to 0.18 € and 0.01 € in the CONV, and 0.29 € and 0.12 € in the ORG. The total milling cost thus amounts to 0.19 € kg^{-1} in the CONV and 0.41 € kg^{-1} in the ORG. This data reveals an increase of over 110% in the ORG, which can be attributed in part to the smaller production scale and in part to additional costs (e.g., certification, dedicated sanitation), which are proportionally more expensive.

Baking represents the stage with the highest cost incidence in absolute terms, contributing 3.68 € kg^{-1} in the CONV and 3.84 € kg^{-1} in the ORG. Although the difference is smaller compared to other stages (+4.30% in the ORG), it is still significant in aggregate terms. Fixed costs are higher in the ORG (2.10 € kg^{-1} compared to 1.64 € kg^{-1} in the CONV), suggesting lower utilisation of facilities or the use of specific processes (such as the use of certified organic ingredients, dedicated sanitation, etc.). Variable costs, on the other hand, are slightly lower in the ORG (1.74 € kg^{-1} compared to 2.04 € kg^{-1} in the CONV).

Discussions

Bread is a fundamental part of diets across the globe, particularly in Europe. Its ingredients and preparation methods vary widely based on local traditions and cultural influences, resulting in diverse textures, flavours,

Table 5. Average production costs of conventional and organic methods across different stages of the Verna wheat supply chain.

	CONV			ORG		
Costs	Farm (€/kg)	Mill (€/kg)	Bakery (€/kg)	Farm (€/kg)	Mill (€/kg)	Bakery (€/kg)
Fixed	-	0.18	1.64	-	0.29	2.10
Variable	0.30-0.45	0.01	2.04	0.40-0.54	0.12	1.74
Total	*0.30-0.45*	*0.19*	*3.68*	*0.40-0.54*	*0.41*	*3.84*

and forms (Notarnicola et al. 2017). To shift away from the current model of high-input agriculture with low nutritional food quality, ancient wheat varieties and their traditional landraces, which have not undergone modern breeding programs, represent a valuable genetic resource. These heritage grains have the potential to contribute significantly to the development of sustainable agricultural systems that minimise external inputs while enhancing the nutritional profile of food products (Roumia et al. 2023; Holka and Kowalska 2025). However, Verna wheat cannot be considered representative of all wheat varieties due to its low yields, which are often around 50% of those of modern varieties. Comparisons between modern and ancient wheat varieties in terms of yield are not advisable, as they may lead to an overestimation of the environmental impact of ancient varieties (Verdi et al. 2022). Nevertheless, comparing the conventional and organic production chains of Verna bread serves as a valuable tool for assessing the environmental performance of different agricultural systems.

Global warming

This impact category provides relevant insights for understanding the environmental effects of anthropogenic activities – specifically food production, as analyzed in this study – on the environment, and more specifically on GW (Brentrup et al. 2004). Contrary to the findings of Camara-Salim et al. (2020) in a study conducted in Spain, which reported that the processing phase contributed approximately one-third of GW relative to the cultivation phase, our results indicate that grain processing accounted for the highest environmental impacts in both systems, representing over 70% of the total, while the cultivation phase contributed less than 30% (Table 4). The lower environmental impact observed in the present study, in comparison to the findings of Camara-Salim et al. (2020), can primarily be attributed to the absence of an irrigation system. Furthermore, the small scale of mills and bakeries considered in this study, which are typical of the Tuscan context and linked to the production of geographically certified bread, results in lower production capacities and, consequently, higher environmental costs per unit of product, compared to larger-scale systems such as those described by Camara-Salim et al. (2020). Nevertheless, our findings are corroborated by Notarnicola et al. (2017), who also highlight the processing phase as a particularly impactful stage in bread production, especially in the Italian context when using ancient wheat varieties (Kulak et al. 2015). In this sense, our results highlight that milling of grains and baking are the most impactful stages in terms of GW. In particular, in the CONV system, the baking phase accounts for approximately 80% of the total environmental impact of bread processing while in the ORG system, more than 90% of the impacts are associated with the baking and milling stages (Figure 3). These impacts are primarily due to the high energy demands of these processes, which inevitably result in significant greenhouse gas emissions. Notably, in the ORG system, milling contributes a substantially larger share of the overall impact compared to the CONV system. This difference is likely related to the smaller scale of infrastructure commonly found in organic supply chains, which are often linked to niche production. Naturally, numerous factors contribute to the environmental burden of the bread production process. For instance, in the cultivation phase, the use of synthetic inputs is closely associated with higher environmental costs, albeit also with potentially increased yields over which impacts can be distributed (Holka 2020). The production context also plays a crucial role; the type of energy sources used (renewable vs. non-renewable) to sustain the production process can significantly influence the overall environmental costs. These findings suggest that by targeting energy consumption – through improved energy use efficiency – and by optimising the type of energy used during milling and baking, the environmental performance of bread production could be substantially improved.

Freshwater ecotoxicity

The primary environmental impacts associated with FE stem from the use of pesticides, fungicides, and fertilisers (Prechsl et al. 2017). Indeed, the CONV agricultural system tends to generate greater impacts compared to the ORG system (Table 4). However, recent studies have highlighted that the use of heavy metals can also significantly contribute to the overall FE. In the CONV system, heavy metal emissions are mainly linked to the production and use of synthetic fertilisers. In contrast, the ORG system relies on copper-based products for seed tanning, which raises concerns due to the environmental implications of copper use (Sydow et al. 2020). Despite this, our findings suggest that the amounts of copper used in

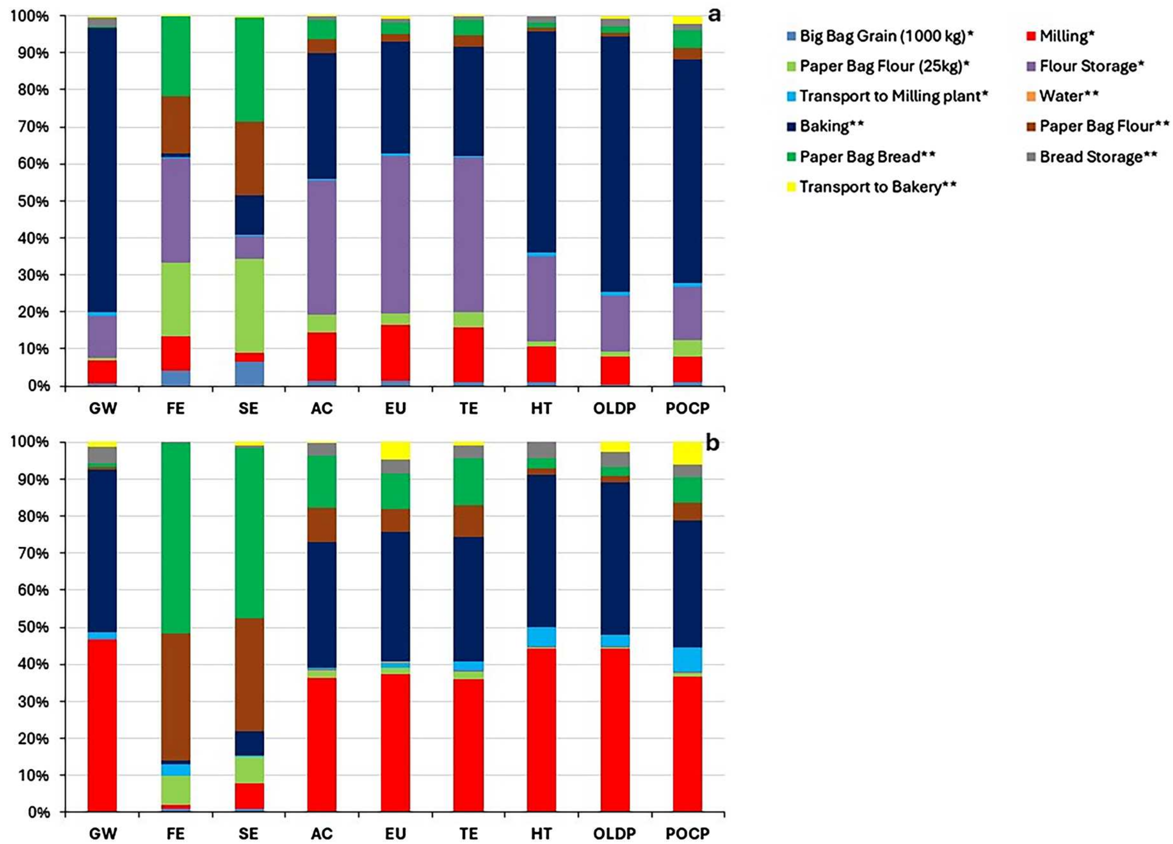

Figure 3. Relative contribution (%) of processing sub-phases to selected impact categories in the Verna bread supply chain under conventional – CONV (a) and organic – ORG (b) systems. Factors marked with '*' to the Milling phase while factors marked with '**' refers to the baking phase. GW = Global Warming; FE = Freshwater Ecotoxicity; SE = Seawater Ecotoxicity; AC = Acidification; EU = Eutrophication; TE = Terrestrial Ecotoxicity; HT = Human Toxicity; OLDP = Ozone Layer Depletion Potential; POF = Photochemical Ozone Creation Potential.

seed tanning, as well as the associated heavy metal emissions resulting from copper extraction and application, do not lead to impacts comparable to those observed in the CONV system. These results align with the observations reported by Camara-Salim et al. (2020), who found similar FE impact values, particularly with respect to the CONV system. In this regard, selecting production inputs with low environmental impacts during their manufacturing phase, combined with a more efficient use of these inputs (e.g., precision farming, use of organic fertilisers, adoption of renewable energy sources), could significantly improve the environmental performance related to FE of bread production. Regarding the processing phase, paper bag production, for both flour and bread packaging, represents the main source of impact of the processing phase, in both systems (Figure 3). This is likely due to the use of heavy metals during the bag manufacturing process (Bandara and Indunil 2022). Additionally, the CONV system shows a moderate contribution to FE from the flour storage phase. In this context, the use of technologies powered by renewable energy sources, as well as eco-friendly packaging materials, could contribute to reducing the environmental impacts of FE.

Seawater ecotoxicity

Consistent with recent literature (Ghasemi-Mobtaker et al. 2020), SE emerges as the most critical impact category across both production systems (Table 4). Specifically, more than two-thirds of the total environmental impacts are attributable to SE, although the ORG system exerts comparatively lower pressure in this category than the CONV system. Similar to FE, SE impacts are predominantly driven by the production and application of synthetic nitrogen- and phosphorus-based fertilisers, which are characteristic of the CONV system.

However, in the ORG system, the use of copper-based inputs may account for the SE impacts observed in this production model (Zhang et al. 2017). As observed for FE, the implementation of fertilisation strategies aimed at enhancing nutrient use efficiency, such as precision farming or the application of slow-release fertilisers, can lead to a notable reduction of the impact of SE associated with wheat cultivation. The integration of practices such as cover cropping or intercropping can play a key role in suppressing weed growth, thereby reducing the reliance on herbicides, which represent a significant source of ecotoxic impact in conventional systems. Similar to FE, the main impacts associated with the processing phase are linked to the use and release of heavy metals and polluting compounds during the production and disposal of paper bags (Figure 3). These substances inevitably pose a threat to ecosystem integrity and contribute to environmental pollution. This highlights the need for a critical evaluation of sustainable packaging solutions that aim to minimise the use of hazardous and polluting substances. Furthermore, the adoption of low-impact packaging materials can contribute on the reduction of SE pressure on the environment. Moreover, the use of renewable energy sources and the adoption of energy-efficient processing systems represent effective strategies for improving the environmental performance of the bread processing phase by reducing energy demand and associated impacts.

Acidification

Acidification mainly results from fossil fuel combustion in power generation and industry, vehicle emissions, and agricultural activities, as highlighted by van Zelm et al. (2015). Our observations highlight a similar contribution to AC of cultivation and processing phases accounting approximately to 50% for CONV and ORG systems. In CONV, this is principally due to the growing use of minerals, synthetic inputs and water soluble fertilisers that are typical of modern agriculture (Kulak et al. 2015). However, the lower impacts from the adoption of organic fertilisers in ORG is partially offset by the greater need of tillage operations, which leads to higher fuel combustion emissions from tractors, as well as by the typically lower yields of organic systems, which reduce the capacity to distribute environmental impacts across the FU of production. For these reasons, although CONV shows generally higher impacts, AC levels during the cultivation phase are similar between CONV and ORG systems (Table 3). Greater differences are observed during the processing phase on which CONV highlighted higher impacts than ORG. Domestic baking tends to generate higher emissions than industrial baking, primarily due to lower energy efficiency and the increased transportation needs associated with decentralised production, often located far from end-markets (Kulak et al. 2015). Our observation suggests that, in the present study, the CONV system exhibited lower efficiency, with higher emissions, acidifying substances, and energy requirements compared to the ORG system. These findings are further supported by the observation that, irrespective of the system analyzed, the primary sources of environmental impact are consistently linked to energy-intensive processes such as milling, baking, and storage (Figure 3). As stated for previous impact categories, improvements in technological practices during both the cultivation and processing phases could significantly enhance the environmental performance of the bread production supply chain. Specifically, optimising input usage presents a promising strategy. On one hand, reducing fertiliser and synthetic inputs application (e.g., through precision farming) could improve the environmental profile of CONV. On the other hand, adopting minimal tillage practices and techniques that preserve organic matter and soil fertility could further reduce the impacts of ORG. Additionally, enhancing processing technologies that utilise renewable energy sources, with high efficiency and low waste production or recycling, could substantially improve the processing phase.

Eutrophication

Eutrophication is the process by which water bodies and soils become excessively enriched with nutrients, primarily nitrogen and phosphorus, leading to elevated biomass production and potential adverse effects such as hypoxia, biodiversity loss, and ecosystem degradation (Rafiee et al. 2024). Consistently with this statement, the cultivation phase was responsible for the main part of the impacts accounting approximately to 85% of total, for both CONV and ORG (Figure 2). The greater EU impact observed in the CONV system is primarily attributed to the higher use of synthetic fertilisers. While some studies have identified manure application on organic farms as a potential contributor to eutrophication (Kulak et al. 2015), this effect is largely influenced by factors such as application rates, soil properties, seasonal patterns, and timing of application. In the present study, this trend was not observed, as organic farms utilised commercial organic fertilisers rather than raw manure (Verdi et al. 2022). The energy consumptions associated with flour and bread production contribute the most on the environmental impacts of EU highlighting the importance to support the development of low-impact technologies of food processing (Notarnicola et al. 2017). Although the processing phase emits compounds that can negatively affect ecosystems, the EU potential associated with resource consumption during grain processing and bread production remains limited. Nevertheless, the energy consumption associated with milling, baking, and storage remains the dominant contributor to environmental impacts in both systems (Figure 3). Consequently, the most effective strategies for mitigating EU and ecosystem degradation are primarily related to improving the efficiency of nitrogen and phosphorus fertiliser use. Precision farming practices, the application of slow-release fertilisers, and crop rotations can significantly enhance nitrogen use efficiency. Similarly, phosphorus use efficiency can be improved through the use of cover crops, monitoring of soil conditions (e.g., pH), and careful selection of application timing and rate.

Terrestrial ecotoxicity

Pesticide applications in agricultural soils, along with the utilisation of sulphuric acid and steam in the conversion stage, are the primary contributors to TE (Ghasemi-Mobtaker et al. 2020). A study conducted in Iran comparing seven different bread baking systems highlighted the relevant impact of processing phase (production of flour, refining of natural gas, and generation of electricity in power plants) on TE (Kheiralipour and Sheikhi 2025). Our observations corroborated these findings since the contributions of processing phase was over 80% and 70% for CONV and ORG, respectively (Figure 2). The main impacts of this phase are produced by milling, storage, and baking energy consumptions. Regarding the cultivation phase, CONV exhibited the highest impacts, primarily due to the application of pesticides and herbicides, which were not used in the ORG system. Nevertheless, the contribution of TE on the total impacts of bread production chain was almost negligible. In fact, the cumulative impacts of TE, HT, OLDP and POCP were 2.28% and 2.44% for CONV and ORG, respectively (Table 4). In this context, the reduction of environmental impacts could be achieved through the optimisation of pesticide application and the enhancement of production efficiency by transitioning to low-energy technologies and incorporating renewable energy sources within the system boundaries.

Human toxicity

This impact category is linked to the production, use and release of heavy metals in air and water bodies (Hauschild and Huijbregts 2015). The CONV system, which relies heavily on synthetic inputs, demonstrates higher environmental impacts compared to the ORG system (Table 4). This is particularly evident in the contribution to HT, primarily associated with emissions from the synthesis of mineral fertilisers and the manufacture of pesticides and herbicides (Taki et al. 2018). Emissions associated with flour storage and baking account for the majority of the processing-related impacts in the CONV system, highlighting the critical role of this phase in the overall environmental footprint of the bread supply chain (Figure 3). In the ORG system, milling and baking are the primary contributors to environmental impact, further confirming that energy consumption plays a key role in determining the environmental sustainability of bread production. Similar to TE, mitigation efforts should focus on optimising the use of agrochemical inputs and enhancing energy efficiency within the agricultural production system. Moreover, the impacts associated with energy consumptions during the processing phase highlights the importance of adopting high-efficiency technologies and renewable energy sources.

Ozone layer depletion potential

Stratospheric ozone depletion results in elevated levels of ultraviolet radiation reaching the Earth's surface, with well-documented detrimental effects on ecosystems, crop productivity, and human health. This impact category is characterised by the release of ozone-depleting substances, with notable contributions from agricultural practices such as fossil fuel combustion, as well as the manufacture and application of synthetic fertilisers and pesticides (Queiros et al. 2015). Furthermore, combustion processes associated with food production systems, including bread manufacturing, can emit halocarbons and other ozone-depleting substances, thereby contributing to stratospheric ozone degradation. Electricity use, depending on its source, may also play a significant role in this impact by influencing the overall emission profile of production systems (Ghasemi-Mobtaker et al. 2020). Resource efficiency and energy consumption optimisation represent the primary mitigation strategies for addressing impacts within OLDP. Despite an apparent predominant influence of the cultivation phase (Figure 2), the impacts associated with OLDP were found to be negligible in both production systems examined (Table 4).

Photochemical ozone creation potential

Ground-level ozone formation results from complex chemical reactions involving NO^x and non-methane volatile organic compounds. Due to the non-linear nature of its formation and sensitivity to environmental factors, estimating its impacts – on health, ecosystems, and materials – remains highly uncertain and variable (Preiss 2015). Since the precursors of ozone formation are generated during the extraction and distribution of fossil fuels, as well as through vehicle emissions and combustion processes, the entire bread production chain is subject to this type of environmental impact. Our results indicate that energy consumption during the milling and baking stages contributes significantly to ozone-related impacts (Figure 2). Therefore, as with other impact categories discussed earlier, transitioning to low-impact production systems that utilise energy-efficient technologies and renewable energy sources is essential.

Economic assessment

Overall, the analysis confirms that the ORG has a more expensive cost structure throughout the entire supply chain, with the greatest discrepancy occurring at the milling stage, which appears to be the main critical point in terms of economic efficiency (Table 5). However, it is important to note that, despite the higher costs associated with organic production, the final price differential per unit product remains relatively modest (8-10%), reinforcing the potential economic sustainability of the model, provided there is consumer demand willing to recognise its added value.

The value chain analysis for bread produced with Verna wheat, reported in Table 6, highlights that the on-farm production phase plays a relatively minor role in the determination of the final retail price. Most of the

Table 6. Comparison of conventional (CONV) and organic (ORG) supply chains in terms of costs and global warming (GW).

	CONV				ORG			
Cost item	Cost (€)	Share of final price (%)	Global warming (CO_2eq kg)	Share of total CO_2eq (%)	Cost (€)	Share of final price (%)	Global warming (CO_2eq kg)	Share of total CO_2eq (%)
Final retail bread price	5.50	100%	–	–	6.50	100%	–	–
VAT (4%)	0.22	4.00%	–	–	0.26	4.00%	–	–
Bakery Profit Margin	0.66	12.00%	–	–	1.05	16.15%	–	–
Baking Costs	2.97	54.00%	0.38	27.54%	2.82	43.38%	0.38	31.15%
Flour Price	0.71	12.91%	–	–	1.02	15.69%	–	–
Mill Profit Margin	0.19	3.45%	–	–	0.27	4.15%	–	–
Milling Costs	0.19	3.45%	0.22	15.94%	0.41	6.31%	0.36	29.51%
Wheat Cost (1.5 kg)[a]	0.68	12.36%	–	–	0.81	12.46%	–	–
Consortium Profit Margin	0.23–0.00	4.00–0.00%	–	–	0.21–0.00	3.00–0.00%	–	–
Wheat Production Cost (1.5 kg)[b]	0.45–0.68	8.00–12.00%	0.78	56.52%	0.60–0.81	9.00–12.00%	0.48	39.34%

Notes. [a]The indicated quantity of 1.5 kg of wheat corresponds to the amount required to produce the flour contained in 1 kg of bread, assuming an average wheat-to-flour conversion yield of approximately 70%.
[b]Heat production costs refer to 1.5 kg of raw wheat, in line with the quantity needed to obtain the flour used in 1 kg of bread.

product's added value is generated during the baking phase, which alone accounts for approximately 70% of the final price. The data also reveal that farmers often receive minimal, if not negligible, margins. Depending on the production method adopted and prevailing market prices at the time of sale, producers may even sell their wheat at a loss. It is important to note that in recent years, both soft and durum wheat prices have exhibited high volatility, with significant repercussions on crop profitability.

The data observed for Verna wheat indicate no substantial improvement in profitability even with the adoption of organic principles. Lower yields in ORG result in higher production costs per unit, and while sales prices are generally higher, they are often insufficient to generate substantial profit margins. However, it should be emphasised that organic farmers benefit from more generous EU subsidies, which can partially offset the lower profitability and contribute to the overall economic viability of organic farming systems.

Conclusions

This study contributes to clarifying the environmental and economic impacts associated with the bread production chain, addressing a topic for which limited literature is currently available. The scarcity of research highlights the relevance and importance of this work. It is important to consider the wide range of wheat varieties – resulting both from genetic improvement and the renewed interest in ancient and traditional cultivars – which introduces substantial variability in the results. This variability arises from differences in yield potential and the diversity of agricultural practices adopted according to specific pedoclimatic conditions. Nevertheless, the quantification of environmental and economic impacts along the bread production chain, under different cultivation regimes, constitutes a matter of critical importance. Such assessments are essential not only for the scientific community, which can leverage this knowledge to foster the transition toward more sustainable agri-food systems, but also for the commercial sector, as they provide a basis for developing equitable and efficient food production strategies that benefit both producers and consumers. Moreover, the findings hold relevance for policymakers, offering evidence-based insights to support the formulation of targeted and effective sustainability policies within the cereal sector.

The type and scale of processing facilities also play a critical role in determining the magnitude of environmental impacts. Smaller-scale plants, typical of traditional productions such as those based on Verna wheat, tend to exhibit higher impacts compared to large-scale industrial systems. Nevertheless, these traditional productions, often based on ancient varieties, are essential for preserving and safeguarding local heritage and dietary traditions, such as the Mediterranean diet.

The adoption of low-impact agronomic practices within a circular economy framework presents a promising strategy for reducing the environmental footprint of Verna bread production. This can be achieved through more efficient use of synthetic inputs, resource recycling, and optimisation of processing technologies.

From an economic perspective, the marginal role of the agricultural phase in value creation along the supply chain is evident, as is the substantial equivalence in terms of profitability between conventional and organic systems. In the case of organic farming, adoption appears to be largely driven by the availability of specific EU subsidies. For organic systems to become independently viable, further market appreciation or a more equitable distribution of subsidies along the supply chain would be necessary.

Future research should focus on the environmental and economic impacts of bread production on a larger scale (i.e., national level) and include additional varieties and market configurations, to strengthen the robustness and transferability of the findings. In fact, the main limit of this study is related to the geographical representation of the study area. While the Verna wheat is an autochthonous variety of the Tuscany region, a study conducted at the national scale – capable of representing the diversity of agricultural systems and processing practices within the bread production chain – could provide insights that are more easily transferable to other contexts. Nevertheless, this type of research constitutes an important step toward the study of traditional production systems and origin-labelled products, which play a significant role in the European food sector.

Overall, this research offers valuable insights for both the scientific and business communities. It shows how sustainability assessments can help shape policies and market strategies that balance environmental goals with economic realities. By linking research to real-world practice, it provides useful guidance for those working to make agri-food systems more sustainable and economically resilient.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

We acknowledge co-funding from NextGeneration EU, in the context of the National Recovery and Resilience Plan,M4C2 Investment 1.4, CN00000022, National Research Centre for AgriculturalTechnologies, CUP B13C22001020007. This resource was co-financed by the NextGeneration EU. The views and opinions expressed are only those of the authorsand do not necessarily reflect those of the European Union or the EuropeanCommission. Neither the European Union nor the European Commission can be heldresponsible for them.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Notes on contributors

Dr. L. Verdi is an assistant professor from the Department of Agriculture, Food, Environment and Forestry (DAGRI) – University of Florence. His research activity is mainly focused on agronomy and agrometeorology. In particular, Dr. Verdi is dedicated on the assessment of greenhouse gas emissions dynamics from the soil-plant-atmosphere system, the analysis of nutrient cycles within agricultural systems, and the evaluation of environmental impacts of agricultural activities, focusing on fertilizer management, short supply chains, and local agricultural production. Moreover, his research involves the study of circular economy systems for valorizing agricultural by-products, maintaining yields, and reducing associated environmental impacts. Dr. Verdi is dedicated to the environmental impact assessment of agricultural activities using the main indicators (CF, WF, LCA, etc.).

Dr. F. Gerini is an assistant professor at the Department of Agriculture, Food, Environment and Forestry (DAGRI) – University of Florence. Her research primarily concerns agri-food economics and marketing, with a strong focus on consumer decision-making processes. She investigates the determinants of food preferences, the effectiveness of sustainability-oriented communication strategies, and the role of geographical origin in shaping purchasing behavior. An additional line of inquiry addresses short food supply chains, analyzing their potential to strengthen producer-consumer relationships and support more resilient rural economies. She has also produced research on the wine sector, including analyses of market performance, consumer preferences for quality and sustainability attributes, and the positioning of PDO and premium wines within modern distribution channels. Her work also examines the structural dynamics of agri-food markets and the trajectories of rural development, with specific attention to factors influencing quality of life in rural areas.

Dr. L. Azzini is a PhD student at the Department of Agriculture, Food, Environment and Forestry (DAGRI) - University of Florence. Dr. Azzini is an expert on the assessment of the environmental impacts of agricultural activities, and he specializes in LCA analysis.

Dr. G. Piracci is an assistant professor at the Department of Land, Environment, Agriculture and Forestry (TESAF), University of Padua. Her research interests lie in agricultural and environmental economics, with a focus on the social and behavioral drivers of sustainable food systems. On the demand side, she studies food and wine consumer behavior. She analyses how sustainability and health-related information, quality schemes and product attributes shape purchasing decisions and the acceptance of innovative products and distribution models, including short and local food supply chains. She also examines how these developments affect food system dynamics and policy decisions. Her research further extends to climate change adaptation and water governance, analyzing socio-economic vulnerability to climate extremes and the design of policy and market-based instruments for water saving and ecosystem conservation. Her empirical work mainly draws on survey-based and experimental designs, particularly discrete choice experiments and related stated preference techniques.

Prof. L. Casini is a full professor at the Department of Agriculture, Food, Environment and Forestry (DAGRI) - University of Florence. His research focuses on rural development policies, models of agricultural multifunctionality, and the competitive strategies of agri-food firms. He examines how agricultural policies, quality certification schemes, and innovation within production systems influence farm performance and sustain the socio-economic vitality of rural territories. A central strand of his work concerns consumer behavior, with particular attention to preferences related to sustainability, environmental attributes, and health-oriented information. He has also conducted extensive research on the wine market, analyzing demand trends, quality-signaling mechanisms, and the strategic positioning of PDO and premium wines. Furthermore, his studies investigate the evolution of food demand, supply-chain organization, and the broader economic and social implications of structural transformations in agriculture.

Prof. S. Orlandini is a full professor at the Department of Agriculture, Food, Environment and Forestry (DAGRI) – University of Florence. His research focuses on agronomy, agrometeorology and agroclimatology, and the promotion and development of applications to support the agro-environment sector. Particularly, the relationships between biotic and abiotic elements of cultural systems (soil, water, climate, crop) have been studied, taking into account the best agronomic management to improve the quality and quantity of production, reducing possible impacts of adversities (frost, soil erosion, diseases). The use of modelling and generally the application of computer science and innovative technologies in agriculture has been strengthened to develop decision support systems for environmental and farm planning and management. Climate change and variability have been studied, analyzing trends, vulnerability, mitigation and adaptation strategies, and impacts on the main crops of national interest. The concept of sustainability has been considered, using different indicators (water and carbon footprint, LCA) as well as the role of renewable energies to mitigate climate change.

References

Annett LE, Muralidharan V, Boxall PC, Cash SB, Wismer WV. 2008. Influence of health and environmental information on hedonic evaluation of organic and conventional bread. J Food Sci. 73(4):H50–H57. https://doi.org/10.1111/j.1750-3841.2008.00723.x

Bandara R, Indunil GM. 2022. Food packaging from recycled papers: chemical, physical, optical properties and heavy metal migration. Heliyon. 8(10). https://doi.org/10.1016/j.heliyon.2022.e10959

Bellassen V et al. 2022. The economic, environmental and social performance of European certified food. Ecol Econom. 191:107244. https://doi.org/10.1016/j.ecolecon.2021.107244

Benincasa P et al. 2016. Eleven-year results on soft and durum wheat crops grown in an organic and in a conventional low input cropping system. Ital J Agron. 11(2):726. https://doi.org/10.4081/ija.2016.726

Brentrup F, Küsters J, Lammel J, Barraclough P, Kuhlmann H. 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology: II. The application to N fertilizer use in winter wheat production systems. Europ J Agron. 20:265–279. https://doi.org/10.1016/S1161-0301(03)00039-X

Brunori G et al. 2016. Are local food chains more sustainable than global food chains? Considerations for assessment. Sustainability. 8(5):449. https://doi.org/10.3390/su8050449

Bux C, Lombardi M, Varese E, Amicarelli V. 2022. Economic and environmental assessment of conventional versus organic durum wheat production in Southern Italy. Sustainability. 14(15):9143. https://doi.org/10.3390/su14159143

Camara-Salim I et al. 2020. Life cycle assessment of autochthonous varieties of wheat and artisanal bread production in Galicia, Spain. Sci Tot Environ. 713:136720. https://doi.org/10.1016/j.scitotenv.2020.136720

Chiriacò MV, Grossi G, Castaldi S, Valentini R. 2017. The contribution to climate change of the organic versus conventional wheat farming: A case study on the carbon footprint of wholemeal bread production in Italy. J Clean Product. 153:309–319. https://doi.org/10.1016/j.jclepro.2017.03.111

Consorzio Gian Pietro Ballatore. 2007. La filiera del grano duro in Sicilia. Edizioni Fotograf.

di Cristofaro M, Marino S, Lima G, Mastronardi L. 2024. Evaluating the impacts of different wheat farming systems through Life Cycle Assessment. J Clean Product. 436:140696. https://doi.org/10.1016/j.jclepro.2024.140696

Erenstein O et al. 2022. Global trends in wheat production, consumption and trade. In: Reynolds M.P., Braun HJ., editor. Wheat improvement. Springer, Cham. https://doi.org/10.1007/978-3-030-90673-3_4

European Commission. 2020. A farm to fork strategy for a fair, healthy and environmentally-friendly food system. COM(2020) 381 final. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0381

Ghasemi-Mobtaker, H., Kaab, A., Rafiee, S., 2020. Application of life cycle analysis to assess environmental sustainability of wheat cultivation in the west of Iran. Energy 193. https://doi.org/10.1016/j.energy.2019.116768

Goucher L, Bruce R, Cameron DD, Lenny Koh SC, Horton P. 2017. The environmental impact of fertilizer embodied in a wheat-to-bread supply chain. Nat Plants. 3(3):1–5. https://doi.org/10.1038/nplants.2017.12

Hauschild MZ, Huijbregts MA. 2015. Introducing life cycle impact assessment, 1–16. Springer Netherlands.

Holka M. 2020. Assessment of carbon footprint and life cycle costs of winter wheat (*Triticum aestivum* L.) production in different soil tillage systems. Appl Ecol Environ Res. 18:5841–5855. https://doi.org/10.15666/aeer/1804_58415855

Holka M, Kowalska J. 2025. Comparative analysis of environmental impacts of wheat and potato production in conventional and organic systems. Ahead of print.

IPCC. 2023. Climate change 2023: synthesis report. In: H. Lee, J. Romero, editor. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change [core writing team]. IPCC; p 35–115. https://doi.org/10.59327/IPCC/AR6-9789291691647

Italian Official Gazette. 2023. Approvazione di una modifica non minore del disciplinare di un nome iscritto nel registro delle denominazioni di origine protette e delle indicazioni geografiche protette «Pane Toscano» (DOP). (23A01403) (GU Serie Generale n.58 del 09-03-2023). https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2023-03-09&atto.codiceRedazionale=23A01403&elenco30giorni=false

Kheiralipour K, Sheikhi N. 2025. Comparing the environmental impacts of seven bread-baking systems. Intern J Environ Sci Technol. 22(6):4951–4960. https://doi.org/10.1007/s13762-024-06174-7

Korsaeth A et al. 2012. Environmental life cycle assessment of cereal and bread production in Norway. Acta Agriculturae Scandinavica, Section A–Animal Science. 62(4):242–253.
Kulak M, Nemecek T, Frossard E, Chable V, Gaillard G. 2015. Life cycle assessment of bread from several alternative food networks in Europe. J Clean Product. 90:104–113. https://doi.org/10.1016/j.jclepro.2014.10.060
Malorgio G, Marangon F. 2021. Agricultural business economics: the challenge of sustainability. Agricult Food Econom. 9:1–4. https://doi.org/10.1186/s40100-020-00175-z
Mukosha CE et al. 2023. The effect of cropping systems on environmental impact associated with winter wheat production—an LCA "cradle to farm gate" approach. Agriculture. 13(11):2068. https://doi.org/10.3390/agriculture13112068
Nemecek T, Dubois D, Huguenin-Elie O, Gaillard G. 2011. Life cycle assessment of Swiss farming systems: Integrated and organic farming. Agric Syst. 104:217–232. https://doi.org/10.1016/j.agsy.2010.10.002
Notarnicola B, Tassielli G, Renzulli PA, Monforti F. 2017. Energy flows and greenhouses gases of EU (European Union) national breads using an LCA (Life Cycle Assessment) approach. J Clean Product. 140:455–469. https://doi.org/10.1016/j.jclepro.2016.05.150
Prechsl UE, Wittwer R, Van Der Heijden MG, Lüscher G, Jeanneret P, Nemecek T. 2017. Assessing the environmental impacts of cropping systems and cover crops: Life cycle assessment of FAST, a long-term arable farming field experiment. Agricultural Systems. 157:39–50.
Preiss P. 2015. Photochemical ozone formation. In: Hauschild M., Huijbregts M., editor. Life cycle impact assessment. LCA compendium – The complete world of life cycle assessment. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9744-3_7
Queiros J, Malca J, Freire F. 2015. Environmental life-cycle assessment of rapeseed produced in Central Europe: addressing alternative fertilization and management practices. J Clean Product. 99:266–274. https://doi.org/10.1016/j.jclepro.2015.03.016
Rafiee M, Abbaspour-Fard MH, Heidari A. 2024. Analyzing sustainability in bread production: A life cycle assessment approach to energy, exergy and environmental footprint. Environ Sci Pollut Res. 31(34):46949–46964. https://doi.org/10.1007/s11356-024-34121-z
Roumia H, Kókai Z, Mihály-Langó B, Csobod ÉC, Benedek C. 2023. Ancient wheats—a nutritional and sensory analysis review. Foods. 12(12):2411. https://doi.org/10.3390/foods12122411
Sacchi G, Belletti G, Biancalani M, Lombardi G, Stefani G. 2019. The valorisation of wheat production through locally-based bread chains: experiences from Tuscany. J Rural Stud. 71:23–35. https://doi.org/10.1016/j.jrurstud.2019.09.006
Sanders J, Brinkmann J, Chmelikova L, Ebertseder F, Freibauer A, Gottwald F, Haub M, Hoppe A, Hauschild M, Hoppe J, et al. 2025. Benefits of organic agriculture for environment and animal welfare in temperate climates. Org Agr. 15:213–231. https://doi.org/10.1007/s13165-025-00493-w.
Seufert V, Ramankutty N, Foley JA. 2012. Comparing the yields of organic and conventional agriculture. Nature. 485(7397):229–232. https://doi.org/10.1038/nature11069
Svanes E., Oestergaard S., Hanssen O. J. 2018. Effects of packaging and food waste prevention by consumers on the environmental impact of production and consumption of bread in Norway. Sustainability. 11(1):43.
Sydow M, Chrzanowski Ł, Hauschild MZ, Owsianiak M. 2020. Influence of metal speciation on soil ecotoxicity impacts in life cycle assessment. J Environ Manage. 266:110611.
Taki M, Soheili-Fard F, Rohani A, Chen G, Yildizhan H. 2018. Life cycle assessment to compare the environmental impacts of different wheat production systems. J Clean Product. 197:195–207. https://doi.org/10.1016/j.jclepro.2018.06.173
Tuomisto HL, Hodge ID, Riordan P, Macdonald DW. 2012. Does organic farming reduce environmental impacts?–A meta-analysis of European research. J Environ Manage. 112:309–320. https://doi.org/10.1016/j.jenvman.2012.08.018
van Zelm R, Roy PO, Hauschild MZ, Huijbregts MA. 2015. Acidification. In: Life cycle impact assessment. Dordrecht: Springer Netherlands; p. 163–176.
Venturi M et al. 2021. Influence of different leavening agents on technological and nutritional characteristics of whole grain breads obtained from ancient and modern flour varieties. Eur Food Res Technol. 247:1701–1710. https://doi.org/10.1007/s00217-021-03740-y
Verdi L, Dalla Marta A, Falconi F, Orlandini S, Mancini M. 2022. Comparison between organic and conventional farming systems using Life Cycle Assessment (LCA): A case study with an ancient wheat variety. Eur J Agron. 141:126638. https://doi.org/10.1016/j.eja.2022.126638
Yu Y, He Y, Zhao X, Zhou L. 2022. Certify or not? An analysis of organic food supply chain with competing suppliers. Ann Oper Res. 314(2):645–675.
Zhang F et al. 2017. Life cycle assessment of diammonium- and monoammonium-phosphate fertilizer production in China. J Clean Prod. 141:1087–1094. https://doi.org/10.1016/j.jclepro.2016.09.107