Cleaner Environmental Systems 20 (2026) 100413

Contents lists available at ScienceDirect

Cleaner Environmental Systems

journal homepage: www.journals.elsevier.com/cleaner-environmental-systems

Life cycle assessment of Sicilian durum wheat: A comparative study of conventional and organic systems

M. Auteri [a], S. Prestigiacomo [a,*], R.N. Mankaa [b], A. Covais [c], M. Traverso [b], G. Di Miceli [a]

[a] Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze, Building 4, 90128, Palermo, PA, Italy
[b] Institute of Sustainability in Civil Engineering, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, 52074, Aachen, Germany
[c] Circular S.R.L., Via Libertà 34, 90141, Palermo, Italy

ARTICLE INFO

Keywords:
LCA
Hard wheat
Primary data
Sustainable agriculture
Environmental impact
Rainfed agriculture
Mediterranean agriculture

ABSTRACT

Durum wheat production plays an indispensable role in sustaining populations, and it occupies an estimated area of 18 million hectares worldwide. The production of this crop requires a large amount of material and energy inputs, affecting the environment in different ways including the emissions of greenhouse gases. In the context of global climate change it is urgent to mitigate the impact of agricultural activities. The aim of this study was to evaluate and compare the environmental impacts of conventional and organic durum wheat grain production systems in Sicily, involving, for the first time, a considerable number of farms, using the Life Cycle Assessment methodology. Primary data were collected from 21 Sicilian farms and a ton was used as the functional unit. A "cradle to farm gate" system boundary was adopted, encompassing both background activities and all inputs for wheat cultivation. Secondary data were used when the primary information was not available; the analysis was carried out using SimaPro 9.5.0.1. The impact was calculated through the CML-IA baseline method, considering 11 impact categories and land use from the Recipe midpoint (H) 2016. The results showed that in all impact categories conventional farming had higher impacts than organic. Furthermore, in most categories for the conventional system, the main affecting factors were fuel, transport, fertilisers and pesticides, while in the organic one only fuel and seeds. Normalized results suggested that marine aquatic ecotoxicity showed the highest values, followed by freshwater ecotoxicity. The results of this study are relevant for evaluating strategies to reduce the environmental impacts associated with durum wheat production.

1. Introduction

Food systems have a big impact on multiple areas of human life, influencing dietary habits, health outcomes, economic stability, socio-cultural structures, and environmental sustainability. Although this sector is essential for human life, it is responsible for climate change, generating around 16.2 Gt CO_2eq in 2022, of which 6.1 Gt of Greenhouse Gas Emissions (GHG) were attributed to agriculture alone (Milne et al., 2025; FAO, 2020).

Simultaneously, global food security is strongly affected by the consequences of climate change, especially on crop yield (Ehsan et al., 2022). The intricate relationship between agriculture and environmental sustainability is characterized by a bidirectional influence where environmental changes both shape and are shaped by agricultural practices (Fanzo and Miachon, 2023). This dynamic interplay highlights the complexity of achieving environmentally sustainable agricultural practices for food production. Understanding these interconnected factors is essential as we address food security and environmental health. Sustainable agriculture, included as target in the Sustainable Development Goals (SDGs), in particular 2.4.1, was presented by all United Nations member countries in 2015, emphasizing its importance in mitigating the environmental impact of agriculture and promoting ecosystem health (Liu, 2023) as well as the achievement of Zero Hunger (2nd SDG). In this context, durum wheat production exemplifies the challenges and opportunities associated with achieving a sustainable agricultural system. It is a cornerstone of global food security, playing an essential role in feeding populations worldwide. It represents one of the most significant staple crops, with an estimated global cultivation area of about 18 million hectares and a total production ranging between 35 and 40 million tons (Grosse-Heilmann et al., 2024). Durum wheat (*T. turgidum* L. ssp. *durum*), the species of interest in this study, is the most cultivated cereal crop in the Mediterranean basin, traditionally

* Corresponding author.
E-mail address: simona.prestigiacomo01@unipa.it (S. Prestigiacomo).

https://doi.org/10.1016/j.cesys.2026.100413
Received 17 October 2025; Received in revised form 4 December 2025; Accepted 11 February 2026
Available online 13 February 2026

grown under rainfed conditions through conventional tillage operations (Tedone et al., 2017). In particular Sicily, the largest island in the Mediterranean, boasts a long and rich agricultural tradition. Durum wheat plays a central role in its economy, culture, and diet. Historically known as the "granary of the Roman Empire" (Cicero, 1935), Sicily is renowned for its ability to produce large quantities of high-quality durum wheat exported throughout the Mediterranean. It is the second Italian region for durum wheat production (the first is Puglia) and based on ISTAT data (Istat, last access April 09, 2025), the cultivated area of durum wheat in Sicily in 2024 was about 280.000 ha, of which about 42.000 ha were cultivated in organic systems in 2023 (Sinab, last access April 09, 2025).

In this context, comparing organic and conventional agriculture in wheat production becomes particularly important. Organic farming is a cultivation method distinguished by the absence of synthetic pesticides and fertilizers, as well as genetically modified organisms (GMOs), according to Regulation (EU) 2018/848. It is based on agricultural practices aimed at promoting soil fertility, biodiversity (Iocola et al., 2021) and ecosystem balance, while ensuring the production of healthy and nutritious food. In the context of wheat production, organic agriculture emerges as a sustainable alternative to conventional farming, offering numerous environmental benefits. However, the absence of pesticide application can result in suboptimal management of weed flora, while the lack of synthetic fertilizer application may restrict the optimal supply of nutrients to the crop, thereby affecting its productivity and overall resilience (Di Mola et al., 2021; Hammad et al., 2020; Ercoli et al., 2011). On the contrary, conventional agriculture, which has been employed for several decades, relies heavily on chemical inputs to achieve higher yields and meet the necessary demand for supporting demographic expansion. Although this system can optimize crop production and maintain a balanced nutrient supply, it does so at the expense of significant environmental impacts, including water pollution and biodiversity loss (Sumberg and Giller, 2022; Foley et al., 2011; Tilman et al., 2002).

2. LCA of wheat grain production: state of the art

The LCA methodology to assess the environmental impact of wheat production has gained increasing attention. Nowadays, even if a systematic review has encompassed different farms located in Italy, significant gaps remain regarding Sicily (Zingale et al. (2022a). Several studies have focused on the impact of rainfed vs irrigated wheat (Pourmehdi and Kheiralipour, 2023; Taki et al., 2018; Fallahpour et al., 2012; Biswas et al., 2008). Others have gained their attention to LCAs on winter wheat production (Kazlauskas et al., 2023; Berthoud et al., 2011) by applying different agronomical practices (González-García et al., 2021; Holka and Bieńkowski, 2020; Shrestha et al., 2020; Holka, 2016). Moreover, there are some studies using LCA to calculate the environmental impact of wheat grain production using different fertilisers (Jiang et al., 2021), or considering the differences between conventional and conservative agriculture in Africa (Mulimbi et al., 2023) and in Italy (Falcone et al., 2019). Finally, some researches have addressed to wheat grain grown in conventional systems, in Iran (Ghasemi-Mobtaker et al., 2020), in Italy (Fantin et al., 2017) or worldwide (Jekayinfa et al., 2015). Different studies such as Ingrao et al. (2018) and Chiriacò et al. (2017) explored the impact of the production of bread in Sicily while Zingale et al. (2022b) focused on the pasta processing phase of durum wheat.

Four papers had as their primary objective the evaluation of the differences between conventional and organic farming systems for wheat grain. In Italy Di Cristofaro et al. (2024), studied the impact of durum wheat in conventional, biodynamic and organic farming systems in central Italy (using varieties such as Senatore Cappelli, Saragolla and Antalis). Verdi et al. (2022) analyzed the impact of soft wheat grain production in Tuscany, specifically about the Verna's variety. Van Stappen et al. (2015) characterized Walloon conventional and organic wheat production systems, while Herrera Huerta et al. (2012), evaluated conventional and organic Chilean wheat production using life cycle assessment (LCA). Finally, there is only one study based in Sicily (Zingale et al., 2024) exploring low-input vs high-input system in a specific case study with only two farms involved in.

In Table S1, the details of these works were added, including area of study, system boundaries, functional units, type of data and the number of indicators used for the calculation of the impact. Despite these extensive LCA studies on wheat production, there remains a significant gap in LCA studies on durum wheat grain in Sicily involving numerous farms and considering different production systems, able to gain the representativity of the analysis. Conducting an LCA of durum wheat cultivation in Sicily involving a significant number of companies is an essential strategic imperative for the region's sustainable development. Sicily has unique agro-ecological and climatic conditions; in addition, the agronomic practices are characterized by simple techniques and rainfed wheat cultivation. This, combined with its historical and economic reliance on wheat, makes understanding the environmental impact of this crop crucial at the regional level. Durum wheat is a cornerstone of Sicilian agriculture and a vital component of the local economy and culture. Furthermore, an LCA study conducted in Sicily's specific context facilitates the identification of best practices and innovation opportunities, such as reduced chemical inputs or the optimized distribution of pesticides and fertilisers. From a strategic standpoint, the results of LCA can inform regional agricultural policies, incentivize sustainable farming methods and attract funding for green innovation, providing a clear roadmap for future actions.

3. Methodology

To conduct the study, the LCA method was used. According to the methodology, four steps were followed: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation of the results. The first phase establishes the main purpose of conducting the assessment, by defining the functional unit (FU), system boundaries, data quality criteria, allocation criteria and any assumptions involved. In the LCI all inputs and outputs data are collected such as resource and energy consumption, produced emissions, products and waste. The LCIA assesses environmental impacts, classifying and characterizing inputs and outputs into impact indicators. Life cycle interpretation, the final phase of an LCA, focuses on analyzing and evaluating the results to identify and evaluate critical information environmental hotspots and mitigation with the aim of finding improvement solutions.

3.1. Goal and scope definition

The main objective of this study was to compare and quantify the environmental performance of Sicilian durum wheat production across organic and conventional farms through an LCA method involving numerous farms. The LCA focused on the field-level production stage and engaged different farms within the Sicilian landscape. Moreover, the research aims to identify and evaluate the major contributors to each impact category for both systems. By identifying critical points in the production process and quantifying different impact categories, this study intends to provide data to support strategic decisions aimed at improving the sustainability of the regional cereal sector.

3.1.1. System boundaries and functional unit

System boundaries included all the steps from cradle to farm gate in both systems (Fig. 1). This approach was justified due to the cultivation phase was recognized as the most contributing step (Zingale et al., 2024). Indeed, the identification of the hotspots in the agricultural process allows farmers to adopt strategies to mitigate the impact. Impacts from the use of fuel, fertilisers and pesticides were included. Additionally, for both systems, the boundaries covered their transport to farmers and the impact of the production and disposal of packaging. Moreover, all background processes (raw materials extractions, production of fuel, lubricating oil, seeds, pesticides, fertilisers) were also included in the study. Considerations for farm infrastructure, machinery production, changes in land use, human labour and maintenance were excluded. Straw was not included in the system boundaries because it was left in the field. Fig. 1 shows the schematic design boundaries of the two farming systems, which differ in the disease control and fertilisation phases, which is absent in organic farming. Emissions from the use of lubricating oil were considered negligible. Moreover, it was assumed that all products (pesticides, fertilisers and seeds) were transported by 3.5–7.5 lorry EURO 4 and the distance covered was from the site of production to the farm gate. In addition, when the farmers produced seeds themselves (in the organic system) it was assumed to be equal to the production of organic seeds.

In LCA studies, it is also important to choose a specific Functional Unit (FU), defined as a quantified performance of a product system to be used as a reference unit (ISO 14040:2006 (International Organization for Standardization, 2006a), 14044:2006 (International Organization for Standardization, 2006b)). In order to assess and compare the environmental impact of the agricultural activity, a yield-based FU was chosen, corresponding to 1 ton of wheat grain.

3.1.2. LCIA methodology and impact categories

The analysis will be carried out using SimaPro – version 9.5.0.1 a standardized software developed by Pré consultants in accordance with the ISO standards.

The majority of the information in this study will consist of primary data, specifically collected for the reference years 2021 and 2022, ensuring a high level of representativeness and accuracy. Data from Ecoinvent v.3.0 will be used in instances where the necessary primary information was unavailable. These secondary data will be limited to background processes such as raw material extraction, fuel production and emissions, as well as the production of lubricating oil, seeds, pesticides, and fertilizers.

The impact will be calculated used CML-IA baseline methodology V3.05/EU2, which is widely used to assess the environmental damage from wheat production (Kazlauskas et al., 2023; Ghasemi-Mobtaker et al., 2020; Taki et al., 2018).

It includes a total of 11 midpoint impact categories: Abiotic Depletion Potential (AD), Abiotic Depletion of fossil fuels (ADff), Global Warming Potential (GWP), Freshwater Aquatic Ecotoxicity Potential (FE), Marine Aquatic Ecotoxicity Potential (ME), Terrestrial Ecotoxicity Potential (TE), Human Toxicity Potential (HT), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Oxidation (PO) and Ozone Layer Depletion (OLD). The above-mentioned impact categories are particularly suitable for wheat production because of their comprehensive approach to assessing a wide range of different environmental impacts. The inclusion of all these categories ensures that the impact of agricultural practices is thoroughly considered, providing a holistic perspective of sustainability. Moreover, Land Use (LU) from Recipe (2016) Midpoint Method (H), which is widely used as references category in wheat systems (Shrestha et al., 2020; Brentrup et al., 2004) will be included.

In order to facilitate an enhanced analysis, the implementation of an optional phase of LCA, the normalization, will be pursued, as it is useful in providing the magnitude of impact for each individual impact category, in relation to a reference unit. The normalization will be based on the total annual environmental impacts generated by the population and activities within the European Union consisting of 25 countries. This is an optional step in LCA analysis to calculate the magnitude of the results of category indicators in relation to reference information, as outlined by ISO 14044 (ISO 14044:2021). In addition, to ensure the quality of results, a sensitivity analysis will be performed varying the value of transportation ±5%, to understand the importance of these contributors. Moreover, for organic systems, it will be conducted also a sensitivity analysis on the seeds, considering the production of organic wheat seeds modelled as Global or for Switzerland, the only two models available in Ecoinvent database.

3.2. Life cycle inventory (LCI)

Primary data related to years 2021/2022 were collected using structured questionnaires addressed to chain employees from 21 farms (14 conventional and 7 organic) all located in Sicily, Italy (Fig. 2). All farms produced durum wheat varieties with rainfed cultivation. Data about cultivated surfaces of farms, altitude, wheat variety and yield are reported in Table 1 Regarding the variety, in some cases in organic they are self-seeds producers (data about variety not available). Each farm consistently used the same agronomic practices over the different years.

Means of the production in conventional and in organic systems were calculated. Also, a one way ANOVA was performed to test the differences between the two types of production and means were separated by Fisher's LSD test.

Data about mechanical practices, pesticides, fertilizers, seeds and all other inputs included in the system boundaries were collected (Tables 2–3). For instance, where primary data were not available, secondary data from Ecoinvent v.3.0 were used.

Emissions from pesticides utilisation were calculated according to Audsley et al. (2003) and Margni et al. (2002). For N and P fertilisers

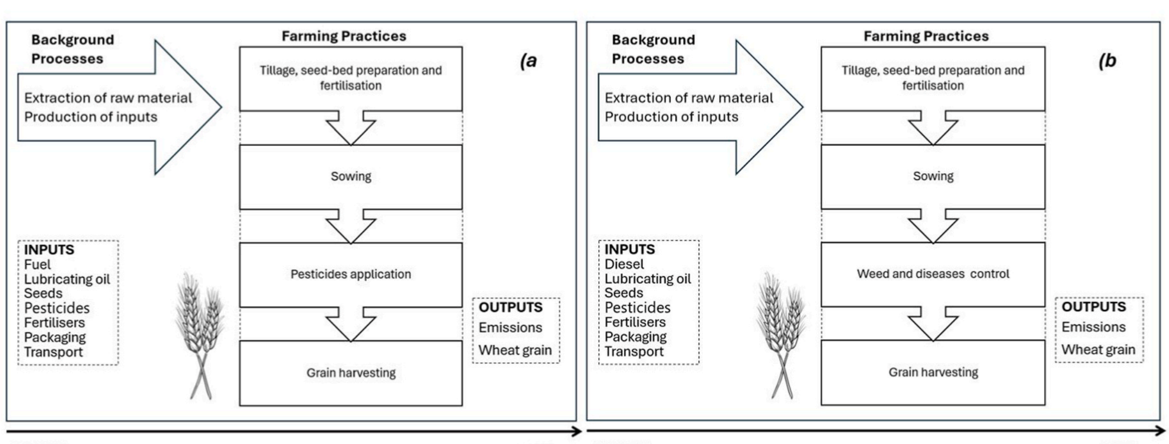

Fig. 1. System boundaries considered in this study. In both systems they were included background processes and farming practices. In *a)* conventional there also are pesticides application, fertilisation, which are absent in *b)* organic.

Fig. 2. Geographical distributions of the farms included in the study; blue represents conventional farming systems, yellow indicates organic farming systems.

Table 1
Range of altitude, wheat cultivated area yield and durum wheat variety, of the farms considered in the present study. A.s.l = above sea level. Means ± SE followed by the same letter in the same column are not significantly different according to Fisher's LSD test ($p \leq 0.05$).

Farming system	Durum wheat variety	Wheat production area range [ha]	Grain yield range [ton ha^{-1}]	Mean	P value
Conventional	Aureo, Arcangelo, Antalis, Core, Iride	8–84	1.75–5.70	$2.94^{a}\pm1.04$	0.022
Organic	Antalis, Core, Simeto	25–150	1.50-2.50	$2^{b} \pm 0.29$	

emissions into the air (dinitrogen monoxide, nitrogen oxides, ammonia) and in water (nitrate and phosphate), were considered, calculated according to Khoshnevisan et al. (2014) for nitrogen and Nemecek et al. (2007) for phosphorus. In order to simplify, these emissions are indicated in the results section as "on field emissions". The inventory analysis of heavy metals was conducted using the SALCA method.

The items listed in Tables 2 and 3 were categorized into several factors in the results section, as outlined below:

- **Fuel**: This factor encompasses both the production, and the on-field emissions of fuel associated with all agricultural practices.
- **Pesticides**: This includes the production of all herbicides and fungicides.
- **Fertilizers**: This refers to the production of all nitrogen (N) and phosphorus (P)-based fertilizers.
- **Seeds**: This factor concerns the production of wheat seeds, both in conventional and organic systems.
- **Transport**: This includes the transportation of fertilisers, pesticides and seeds between production sites and the farm.
- **Packaging**: This refers to the production of packaging used for pesticides, fertilizers, and seeds.
- **Lubricants**: This encompasses the production of lubricants for tractors.

Table 2
Life Cycle Inventory per ton of durum wheat grain production in Sicily in conventional.

Items	Unit	CONV			Description
		Range		Mean	
Field operations	MJ	3.85E+02	1.21E+03	7.52E+02	It includes all tillage operations, seedling and harvesting
Lubricating Oil	kg	2.79E-02	9.08E-02	5.60E-02	It includes the production of lubricating oil used in tractors
Fluroxypyr + Clopyralid + MCPA	l	0.00E+00	7.50E-01	2.74E-01	Pesticides (herbicide)
Mesosulfuron-methyl + Iodosulfuron-methyl-sodium + Mefenpyr-diethyl	l	0.00E+00	8.57E-01	3.67E-01	Pesticides (herbicide)
2,4 D + MCPA	l	0.00E+00	4.57E-01	1.22E-01	Pesticides (herbicide)
Sodium lauryl ether sulphate	l	0.00E+00	5.71E-01	1.85E-01	Wetting agent for pesticides
Pinoxaden + Clodinafop-propargyl + cloquintocet-mexyl	l	0.00E+00	3.77E-01	6.51E-02	Pesticides (herbicide)
Azoxystrobin	l	0.00E+00	1.99E-01	2.42E-02	Pesticides (fungicide)
2,4 D + Florasulam	l	0.00E+00	2.14E-01	1.53E-02	Pesticides (herbicide)
Pinoxaden + cloquintocet-mexyl	l	0.00E+00	2.34E-01	1.67E-02	Pesticides (herbicide)
Seeds	kg	3.51E+01	1.14E+02	7.36E+01	Durum wheat seeds
Sedaxane + Fludioxonil + Difenoconazole	l	7.57E-02	2.47E-01	1.59E-01	Pesticides (fungicide)
N fertilizer	kg	1.75E+01	1.14E+02	5.86E+01	It considers all types of N fertilizers
N:P_2O_5 fertilizer	kg	0.00E+00	1.14E+02	4.26E+01	It considers all types of NP fertilizers
Transport	kg*km	4.22E+05	1.76E+06	1.02E+06	It covers the transport between the production sites of pesticides, fertilizers, seeds and the farm
Packaging	kg	5.73E-01	1.71E+00	1.07E+00	It includes packaging of seeds, fertilizers, pesticides

Table 3
Life Cycle Inventory per ton of durum wheat grain production in Sicily in organic.

Items	Unit	ORG			Description
		Range		Mean	
Field operations	MJ	5.76E+02	9.56E+02	7.75E+02	It includes all tillage operations, seedling and harvesting
Lubricating Oil	kg	1.88E-02	1.15E-01	6.18E-02	It includes the production of lubricating oil used in tractors
Seeds	kg	8.00E+01	1.33E+02	1.02E+02	Organic durum wheat seeds
Transport	kg*km	0.00E+00	1.26E+03	1.79E+02	It covers the transport between the production sites of seeds and the farm
Packaging	kg	0.00E+00	2.40E-01	3.43E-02	It includes packaging of seeds

4. Results

The results of the analysis are presented in Table 4 which reports the mean values of twelve environmental impact categories for organic and conventional wheat production.

The analysis of the different categories of environmental impact highlights a substantial reduction associated with the organic production system compared to the conventional one. In particular, the categories that showed a major difference between the two systems were OLD and AD, which represented a difference of two orders of magnitude. The GWP, similar to FE, TE, PO, ADff showed a difference of one order of magnitude. For HT and ME the reduction ranged from 78 to 84%. Moreover, LU had the smallest difference (16%) between the two systems compared across all categories.

Considering an in-depth analysis of the relative contributions of the different factors in conventional systems, fuel, pesticides, fertilizers and transport had a significant impact on all categories, although their contribution was distributed differently (Fig. 3, Table 5, Table 6).

To enhance clarity and interpretability, impact categories have been grouped according to their primary drivers. In detail, for both systems, seeds mostly affected LU, while for conventional systems, pesticides were identified as the dominant driver in OLD (around 93% of the total impact) and in AD, accounting for approximately 78% of the relative contribution.

Moreover, the impact of transport was predominant in ADff, GWP, FE and PO with values ranged from approximately 33 to 56%. Furthermore, for ME the major contributors were fertilisers, with a value of 39%. On field emissions significantly affected only EP (around 63%), AP (around 53%) and accounted for a value of about 12% in GWP, even though other factors such as transport and fertilisers also contribute to the impact in this category. Seeds accounted for most of the impact in TE, around 39%. With regard to organic farming, given the limited number of inputs, the contributors were identified as fuel, which was responsible for the majority of the impact in AD, ADff, GWP, OLD, HT, FE, ME, PO and seeds, contributing to TE, AP and EP.

Across most impact categories, lubricant and packaging were found to have a negligible influence on both systems.

The results of the sensitivity analysis are reported in table S2 and S3, only for ADff and GWP, because these were the categories most affected by changes in transport. The values are represented as mean percentages. For conventional systems, the difference was about ±1% with respect to the real value. For organic systems it was around 0.06% for GWP and around 0.05% for ADff, reflecting the differences in contributors in these two systems. Regarding the production of organic wheat seeds modelled as Global or for Switzerland, the results expressed as mean percentage, are reported in Tab S.4. Data are represented only for the most affected categories, eutrophication and land use, with respective differences about −0.6% and −0.12%.

The results of normalization are indicated in Fig. 4 and table S5. To facilitate the interpretation of the data, the mean of the normalized results was calculated. The findings of normalization indicated that for both farming systems, ME was the dominant impact category, followed by FE and ADff. These results are related to the use of pesticides and fertilizers that affect the two water ecotoxicity categories, followed by the use of the fuel for transport and for field operations, related to ADff.

Furthermore, PO was negligible, demonstrating minimal impact in this category. Across all environmental impact categories considered, both farming systems exhibited lower impacts for ODP, HT and TE. In certain instances, the environmental impact of organic farming approached zero.

Table 4
Average values of the impact categories for a ton of organic and conventional wheat production with their specific units and the percentage decrease of organic farms compared to conventional farms.

Impact Category	Unit	Conv	Org	% Decrease
LU	m^2a crop eq	2.44E+02	2.05E+02	15.9
EP	kg PO_4^{3-} eq	4.40E+00	1.45E+00	67.2
TE	kg 1,4-DB eq	1.14E+01	2.54E+00	77.6
FE	kg 1,4-DB eq	3.79E+02	7.51E+01	80.2
AP	kg SO_2 eq	1.10E+01	1.94E+00	82.4
ME	kg 1,4-DB eq	7.76E+05	1.20E+05	84.6
PO	kg C2H4 eq	2.41E-01	3.47E-02	85.6
HT	kg 1,4-DB eq	8.79E+02	1.23E+02	86.0
GWP	kg CO_2 eq	1.15E+03	1.50E+02	86.9
ADff	MJ	1.37E+04	1.56E+03	88.6
AD	kg Sb eq	2.65E-02	9.20E-04	96.5
OLD	kg CFC-11 eq	2.39E-04	1.58E-06	99.3

* Percentage of decrease was calculated as the difference between the value in conventional and organic, divided by the value in conventional, and multiplied by 100. Legend: AD = Abiotic Depletion Potential, ADff = Abiotic Depletion of fossil fuels, GWP = Global Warming Potential, OLD = Ozone Layer Depletion, HT = Human Toxicity Potential, FE = Freshwater Aquatic Ecotoxicity Potential, ME = Marine Aquatic Ecotoxicity Potential, TE = Terrestrial Ecotoxicity Potential, PO = Photochemical Oxidation, AP = Acidification Potential, EP = Eutrophication Potential, LU = Land use.

5. Discussion

Organic systems typically involve fewer external inputs but may sometimes exhibit reduced yields (Wilbois and Schmidt, 2019; Herrera Huerta et al., 2012), potentially lowering the environmental benefits per unit of final product (Di Cristofaro et al., 2024; Blengini and Busto, 2009). Conversely, as demonstrated by the results of this study, organic farming is associated with a lower environmental impact compared to conventional systems according to Meier et al. (2015). In the specific context of the Sicilian production system, even if the yield difference was significant, the organic production showed relatively competitive values, reducing the environmental trade-offs typically associated with lower production. The differences in land use between the two systems, could depend on the wheat yield. Generally, it was observed that an increase in yield corresponds to a decrease in land use (Kheiralipour et al., 2024; Brentrup et al., 2004). However, as observed by Armengot et al. (2011), this category is strongly affected by agricultural practices that could significantly differ between farms. According to our research, in this study the land use was higher in conventional fields because of the high use of pesticides. Considering the other impact categories, our analysis aligns with a comprehensive review conducted by Kheiralipour et al. (2024), in which there were considered irrigation, tillage methods, and fertilizer impacts alongside the conventional versus organic systems. Specifically, our findings for TE, AP and EP fall within the ranges defined in their literature review for both systems.

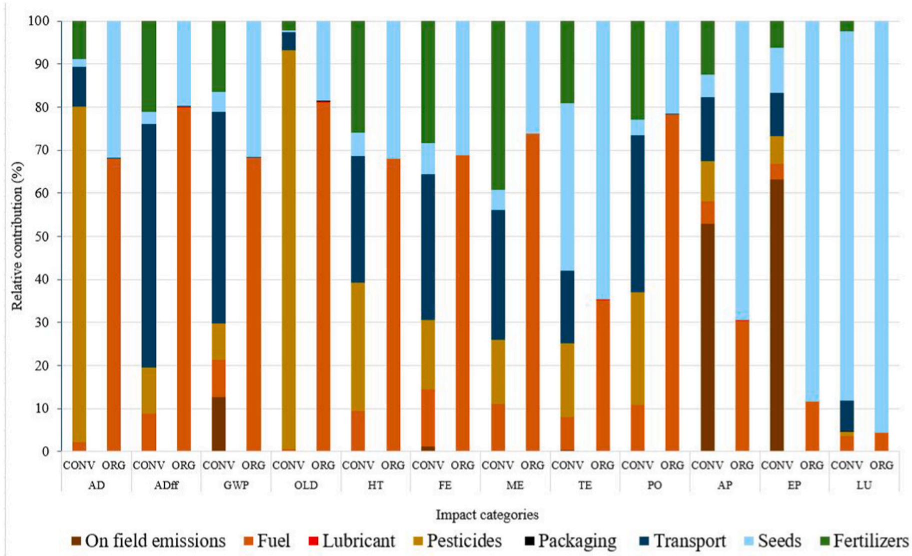

Fig. 3. Average values of relative contributions (%) of all factors both in conventional and organic systems, considering all factors involved in the process, for a ton of wheat grain. Legend: AD = Abiotic Depletion Potential, ADff = Abiotic Depletion of fossil fuels, GWP = Global Warming Potential, OLD = Ozone Layer Depletion, HT = Human Toxicity Potential, FE = Freshwater Aquatic Ecotoxicity Potential, ME = Marine Aquatic Ecotoxicity Potential, TE = Terrestrial Ecotoxicity Potential, PO = Photochemical Oxidation, AP = Acidification Potential, EP = Eutrophication Potential, LU = Land use.

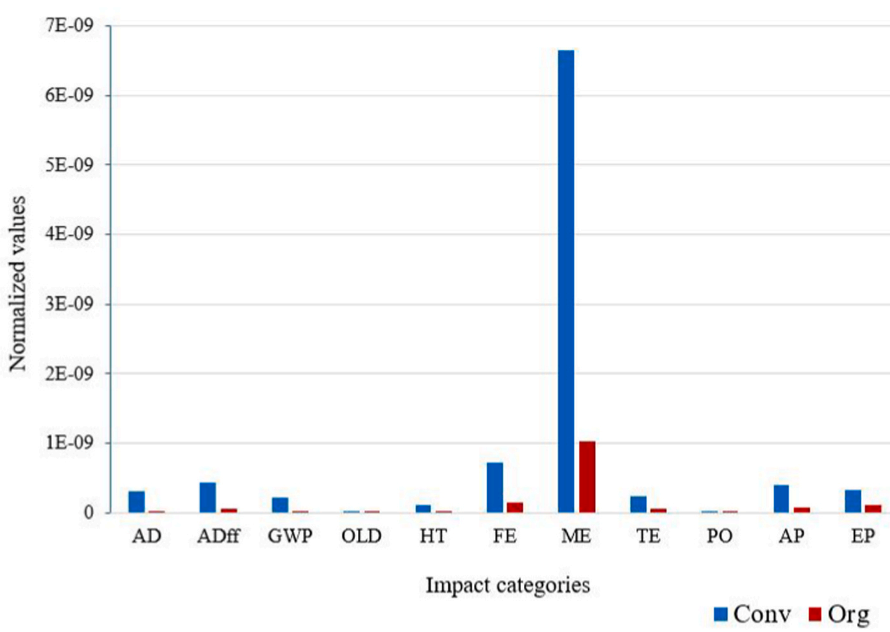

Fig. 4. Mean of normalized values for all impact categories. Legend: AD = Abiotic Depletion Potential, ADff = Abiotic Depletion of fossil fuels, GWP = Global Warming Potential, OLD = Ozone Layer Depletion, HT = Human Toxicity Potential, FE = Freshwater Aquatic Ecotoxicity Potential, ME = Marine Aquatic Ecotoxicity Potential, TE = Terrestrial Ecotoxicity Potential, PO = Photochemical Oxidation, AP = Acidification Potential, EP = Eutrophication Potential.

Concerning AP, the value in conventional systems was higher than the data reported by Holka et al., (2016) in a study conducted between two farms, where the mean of impacts was 5.6 kg SO_2 eq. per ton of wheat grain. The value recorded for EP in conventional farming remains within the limit reported by Herrera Huerta et al. (2012). In their study, the total impact associated with eutrophication in conventional farming reached 4.8 kg PO_4 eq per ton of grain. However, it is higher than the average impact between two conventional farms reported by (Holka et al., 2016) which was 1.5 kg PO_4 eq per ton of grain.

Conversely, for ADff, GWP, OLD, HT, FE and ME, our calculated values in conventional systems were higher than the maximum values cited by Kheiralipour et al. (2024).

ME results are slightly higher than the review's references: the value reported for the conventional system exceeds the mean of over 210 farms in Iran, where an average impact on ME of about 2.75×10^5 kg 1,4-DB per ton of wheat grain was recorded (Taki et al., 2018), and also data referred by Kheiralipour et al. (2024) that found impacts of approx. 3.20×10^5 kg 1.4-DB eq. per ton. This is primarily attributable to the use of synthetic fertilisers, which are major contributors to ME impacts in conventional systems.

The variations observed could be explained by the fact that, although the other studies had a similar assessment of the agricultural practices carried out for wheat grain production, Sicilian farming methods are different from those of other regions and countries. The number of

Table 5
Average values of relative contributions for all factors in conventional farming systems in all impact categories, referred to one ton of wheat grain. Legend: AD = Abiotic Depletion Potential, ADff = Abiotic Depletion of fossil fuels, GWP = Global Warming Potential, OLD = Ozone Layer Depletion, HT = Human Toxicity Potential, FE = Freshwater Aquatic Ecotoxicity Potential, ME = Marine Aquatic Ecotoxicity Potential, TE = Terrestrial Ecotoxicity Potential, PO = Photochemical Oxidation, AP = Acidification Potential, EP = Eutrophication Potential, LU = Land use.

		Factors							
Impact categories	Units	On field emissions	Fuel	Lubricant	Pesticides	Packaging	Transport	Seeds	Fertilisers
AD	kg Sb eq	0.00E+00	6.07E-04	7.17E-07	2.06E-02	9.58E-07	2.48E-03	4.41E-04	2.36E-03
ADff	MJ	0.00E+00	1.21E+03	3.35E+00	1.46E+03	4.01E+00	7.73E+03	3.78E+02	2.89E+03
GWP	kg CO_2 eq	1.46E+02	9.94E+01	8.34E-02	9.64E+01	2.78E-01	5.63E+02	5.37E+01	1.88E+02
OLD	kg CFC-11 eq	0.00E+00	1.24E-06	4.10E-09	2.21E-04	6.57E-09	1.02E-05	9.60E-07	5.10E-06
HT	kg 1,4-DB eq	1.50E+00	8.12E+01	8.13E-02	2.62E+02	1.90E-01	2.58E+02	4.80E+01	2.28E+02
FE	kg 1,4-DB eq	4.45E+00	5.02E+01	3.88E-02	6.09E+01	1.54E-01	1.28E+02	2.81E+01	1.07E+02
ME	kg 1,4-DB eq	4.64E-02	8.57E+04	7.80E+01	1.15E+05	3.53E+02	2.34E+05	3.70E+04	3.04E+05
TE	kg 1,4-DB eq	3.72E-02	8.72E-01	7.88E-04	1.96E+00	2.53E-03	1.91E+00	4.43E+00	2.17E+00
PO	kg C_2H_4 eq	0.00E+00	2.64E-02	2.67E-05	6.31E-02	1.10E-04	8.79E-02	8.32E-03	5.55E-02
AP	kg SO_2 eq	5.83E+00	5.74E-01	3.29E-04	1.02E+00	1.31E-03	1.65E+00	5.61E-01	1.38E+00
EP	kg PO_4^{3-} eq	2.78E+00	1.63E-01	8.95E-05	2.84E-01	2.08E-03	4.38E-01	4.65E-01	2.72E-01
LU	m^2a crop eq	0.00E+00	8.74E+00	2.26E-03	2.75E+00	5.00E-01	1.69E+01	2.09E+02	6.05E+00

Table 6
Average values of relative contributions of all factors in organic farming systems in all impact categories, referred to one ton of wheat grain. Legend: AD = Abiotic Depletion Potential, ADff = Abiotic Depletion of fossil fuels, GWP = Global Warming Potential, OLD = Ozone Layer Depletion, HT = Human Toxicity Potential, FE = Freshwater Aquatic Ecotoxicity Potential, ME = Marine Aquatic Ecotoxicity Potential, TE = Terrestrial Ecotoxicity Potential, PO = Photochemical Oxidation, AP = Acidification Potential, EP = Eutrophication Potential, LU = Land use.

		Factors				
Impact categories	Units	Fuel	Lubricant	Seeds	Packaging	Transport
AD	kg Sb eq	6.25E-04	7.92E-07	2.93E-04	8.44E-08	4.35E-07
ADff	MJ	1.25E+03	3.70E+00	3.09E+02	2.55E-01	1.36E+00
GWP	kg CO_2 eq	1.02E+02	9.20E-02	4.75E+01	2.37E-02	9.88E-02
OLD	kg CFC-11 eq	1.28E-06	4.53E-09	2.92E-07	6.74E-10	1.79E-09
HT	kg 1,4-DB eq	8.36E+01	8.97E-02	3.93E+01	1.80E-02	4.53E-02
FE	kg 1,4-DB eq	5.17E+01	4.28E-02	2.34E+01	1.52E-02	2.25E-02
ME	kg 1,4-DB eq	8.83E+04	8.60E+01	3.12E+04	3.38E+01	4.11E+01
TE	kg 1,4-DB eq	8.98E-01	8.70E-04	1.64E+00	2.58E-04	3.34E-04
PO	kg C_2H_4 eq	2.72E-02	2.95E-05	7.50E-03	1.04E-05	1.54E-05
AP	kg SO_2 eq	5.91E-01	3.63E-04	1.35E+00	1.22E-04	2.89E-04
EP	kg Sb eq	1.68E-01	9.88E-05	1.28E+00	2.32E-04	7.68E-05
LU	m^2a crop eq	9.00E+00	2.50E-03	1.96E+02	5.80E-02	2.97E-03

inputs may vary due to differing agro-ecological conditions.

An analysis of the various contributing factors revealed that the primary drivers were fuel, transport, pesticides and fertilisers in conventional farming, and seeds and fuel in organic farming. Our data are consistent with the findings of Di Cristofaro et al. (2024) and Holka et al., (2016), who highlighted that fertilizers play a major role in the environmental impacts related to ecosystem quality. Additionally, several authors (Mukosha et al., 2023; Verdi et al., 2022) identified fertilisers manufacturing as one of the main factors, followed by mechanical practices including fuel burning. According to our results, the main contributions to the ecosystem quality are also related to pesticide production (Taki et al., 2018; De Backer et al., 2009). The production of both pesticides and fertilisers requires a significant amount of energy and materials from non-renewable resources, such as natural gas and minerals. While these chemicals protect crops from pests, they also contribute to environmental degradation.

Moreover, the industrial processes involved strongly influenced human health. Indeed, a reduction in the use of chemicals (fertilisers, pesticides) could be an effective strategy to decrease the impact of wheat cultivation (Verdi et al., 2022).

Another significant factor is the fuel; its production uses a great deal of energy and involves non-renewable resources. Furthermore, mechanical practices in agriculture are recognized as a significant source of environmental impact on human health and resources (Guo, 2012). According to our results, Ingrao et al. (2018) recognized the transport of products as a main factor, with also the agricultural phase and Biswas et al. (2008) indicates the transportation of inputs as a main contributor to GWP.

Seeds influenced only a few impact categories, mostly land use, probably considering that, in comparison to the other contributors considered in this study, the production of seeds required a larger area, even if there is a gap of knowledge in literature. Regarding terrestrial ecotoxicity, our results align with the results obtained by Falcone et al. (2019) and Verdi et al. (2022) highlighting the substantial environmental burden associated with seed production.

It should be noted that the estimates of seed-related emissions in organic farming may have been slightly overestimated, as the data were obtained from secondary sources (databases), as mentioned in paragraph 3.1.1. as well as the emissions for transport, based on an assumption.

Finally, on-field emissions mostly affected EP, AP and, to a lesser extent, GWP. Regarding eutrophication, this aspect was identified as one of the main environmental challenges associated with agriculture. This data is consistent with the findings of Verdi et al. (2022) and Holka et al., (2016). In fact, inefficient phosphorus (P) use, especially through agricultural runoff and erosion, exacerbates eutrophication, leading to harmful algal blooms and oxygen depletion, which degrades water quality (Liu et al., 2008). The same factor contributed to a different percentage of GWP, as found by Fallahpour et al. (2012). Moreover, as demonstrated by Taki et al. (2018) more than 60% of acidification was influenced by the emissions from the use of fertilisers.

Referring to Prado et al. (2017), normalization references reveal that a single impact category, marine aquatic ecotoxicity (ME), was predominant, followed by freshwater aquatic ecotoxicity (FE) and abiotic depletion of fossil fuels (ADff) according to the CML baseline method. This observation aligns with our study and findings reported in other literature concerning wheat production (Verdi et al., 2022). White and Carty (2010) suggested that the differences in values may be due to impact categories with high normalization factors resulting in relatively small, normalized results. Consequently, categories with low normalization factors generate comparatively higher normalized results (ISO 14074:2024 (International Organization for Standardization, 2022)). The normalized value of wheat production should, therefore, be interpreted as a measure of impact relative to the total annual impact of an individual. This interpretation differs significantly from perceiving the result as an indicator of the importance of the impact category for the product under examination. It is essential to consider these limitations when interpreting normalized results to avoid basing improvement assessment interventions solely on these outcomes.

6. Conclusion

Based on the study conducted, organic wheat production in the specific context of Sicily showed a clear reduction of environmental impacts compared to conventional wheat production in all categories analyzed, despite lower average yields. Analysis of the relative contributions identified fuel, transport, pesticides and fertilizers as key impact drivers in the conventional system. In the organic system, fuel remains a significant contributor. Notably, seed production also emerged as a relevant factor in this system, especially for LU. The absence of synthetic agrochemicals reduced the overall environmental impact. In both systems, the effect of lubricants and packaging was found to be negligible in all categories. The normalization phase allowed the magnitude of the impacts to be contextualized. Consistent with previous research in the literature, ME and FE were identified as impact categories most affected by wheat production. Tudor et al. (2023) indicates that in Italy, in contrast to other EU countries, the correlation between the amount of fertilizers used and the average wheat production is negligible, suggesting a less intensive use of inputs. In fact, it should be noted that the values found for many impact categories in conventional agriculture in Sicily suggest that the durum wheat production system in this region is not extremely intensive. While fuel efficiency remains an area for potential improvement in organic systems, the study suggests that the transition from conventional to organic wheat production offers an important opportunity to mitigate the environmental burdens associated with agriculture and promoting more sustainable food systems. Despite these results, it is clear that the transition to the organic systems is long, difficult and it would require strategies to increase the yields. This study could be a first step to developing practical actions for farmers as optimizing mechanization and timely soil management for a more sustainable agriculture, as highlighted by Verdi et al. (2022). Moreover, it could be important for policymakers to boost buying from local producers, in order to reduce the amount of transport. However, it could be fundamental to financially support the farmers, in applying new technologies, such as agriculture 4.0 and digital technologies, fostering knowledge exchange, collaboration, and innovation in sustainable farming (Marraccini et al., 2024). These results represent the first step to collecting LCA regional-specific data in order to identify environmental burdens for durum wheat production in mediterranean regions and create a regional specific dataset useful for all stakeholders. Indeed, the differences with other studies in Italy (Di Cristofaro et al., 2024; Verdi et al., 2022) underlined the need to carry out regional LCA studies on wheat grain production to obtain results that are more representative of local characteristics and peculiarities of the specific territory.

CRediT authorship contribution statement

M. Auteri: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **S. Prestigiacomo:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **R.N. Mankaa:** Writing – review & editing, Validation, Supervision, Software. **A. Covais:** Writing – review & editing, Conceptualization. **M. Traverso:** Writing – review & editing, Validation, Supervision, Resources, Conceptualization. **G. Di Miceli:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Funding

This study was supported by project NODES which has received funding from the MUR - M4C2 1.5 of PNRR funded by the European Union - NextGenerationEU (Grant agreement no. ECS00000036).

Declaration of competing interest

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2026.100413.

Data availability

Data will be made available on request.

References

Audsley, E., Alber, S., Clift, R., Cowell, S., Crettaz, P., Gaillard, G., Hausheer, J., Jolliett, O., Kleijn, R., Mortensen, B., Pearce, D., Roger, E., Teulon, H., Weidema, B., Zeijts, H. van, 2003. Harmonistion of Environmental Life Cycle Assessment for Agriculture, p. 107. Final Report. Concerted Action AIR3-CT94-2028.

Armengot, L., José-María, L., Blanco-Moreno, J.M., Bassa, M., Chamorro, L., Sans, F.X., 2011. A novel index of land use intensity for organic and conventional farming of Mediterranean cereal fields. Agron. Sustain. Dev. 31 (4), 699–707.

Berthoud, A., Maupu, P., Huet, C., Poupart, A., 2011. Assessing freshwater ecotoxicity of agricultural products in life cycle assessment (LCA): a case study of wheat using French agricultural practices databases and USEtox model. Int. J. Life Cycle Assess. 16, 841–847. https://doi.org/10.1007/s11367-011-0321-7.

Biswas, W.K., Barton, L., Carter, D., 2008. Global warming potential of wheat production in Western Australia: a life cycle assessment. Water Environ. J. 22, 206–216. https://doi.org/10.1111/j.1747-6593.2008.00127.x.

Blengini, G.A., Busto, M., 2009. The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). J. Environ. Manag. 90, 1512–1522. https://doi.org/10.1016/j.jenvman.2008.10.006.

Brentrup, F., Küsters, J., Kuhlmann, H., Lammel, J., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment methodology: I. Theoretical concept of a LCA method tailored to crop production. Eur. J. Agron. 20 (3), 247–264.

Chiriacò, M.V., 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. Prod. 153, 309–319. https://doi.org/10.1016/j.jclepro.2017.03.111.

Cicero, M.T., 1935. In: Verrem, Actio Secunda, Second Verrine oration. CUP Archive.

De Backer, E., Aertsens, J., Vergucht, S., Steurbaut, W., 2009. Assessing the ecological soundness of organic and conventional agriculture by means of life cycle assessment (LCA): a case study of leek production. Br. Food J. 111, 1028–1061. https://doi.org/10.1108/00070700910992916.

Di Cristofaro, M., Marino, S., Lima, G., Mastronardi, L., 2024. Evaluating the impacts of different wheat farming systems through life cycle assessment. J. Clean. Prod. 436, 140696. https://doi.org/10.1016/j.jclepro.2024.140696.

Di Mola, I., Ottaiano, L., Sacco, A., Senatore, M., Mori, M., 2021. Organic versus mineral fertilization: assessing of yield and quality of durum wheat in marginal lands. Ital. J. Agron. 16, 1855. https://doi.org/10.4081/ija.2021.1855.

Ehsan, N., Hoogenboom, G., Qamar, M.K., Wilkerson, C.J., Wajid, S.A., Aziz, F., 2022. Climate change risk perception and adaptation to climate smart agriculture are required to increase wheat production for food security. Ital. J. Agron. 17, 2129.

Ercoli, L., Lulli, L., Arduini, I., Mariotti, M., Masoni, A., 2011. Durum wheat grain yield and quality as affected by S rate under Mediterranean conditions. Eur. J. Agron. 35, 63–70. https://doi.org/10.1016/j.eja.2011.03.007.

Falcone, G., Stillitano, T., Montemurro, F., De Luca, A.I., Gulisano, G., Strano, A., 2019. Environmental and economic assessment of sustainability in Mediterranean wheat production 845.4Kb. https://doi.org/10.15159/AR.19.011.

Fallahpour, F., Aminghafouri, A., Ghalegolab Behbahani, A., Bannayan, M., 2012. The environmental impact assessment of wheat and barley production by using life cycle assessment (LCA) methodology. Environ. Dev. Sustain. 14, 979–992. https://doi.org/10.1007/s10668-012-9367-3.

Fantin, V., Righi, S., Rondini, I., Masoni, P., 2017. Environmental assessment of wheat and maize production in an Italian farmers' cooperative. J. Clean. Prod. 140, 631–643. https://doi.org/10.1016/j.jclepro.2016.06.136.
Fanzo, J., Miachon, L., 2023. Harnessing the connectivity of climate change, food systems and diets: taking action to improve human and planetary health. Anthropocene 42, 100381. https://doi.org/10.1016/j.ancene.2023.100381.
FAO, 2020. The share of agriculture in total greenhouse gas emission. In: Global, Regional and Country trends1990–2017, vol. 1. FAOSTAT Analytical Brief Series No, Rome.
Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. https://doi.org/10.1038/nature10452.
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, 116768. https://doi.org/10.1016/j.energy.2019.116768.
González-García, S., Almeida, F., Moreira, M.T., Brandão, M., 2021. Evaluating the environmental profiles of winter wheat rotation systems under different management strategies. Sci. Total Environ. 770, 145270. https://doi.org/10.1016/j.scitotenv.2021.145270.
Grosse-Heilmann, M., Cristiano, E., Deidda, R., Viola, F., 2024. Durum wheat productivity today and tomorrow: a review of influencing factors and climate change effects. Resources, Environment and Sustainability 17, 100170.
Guo, M., 2012. LCA of wheat agro-eco-system. In: Life Cycle Assessment (LCA) of Light-Weight Eco-Composites. Springer Theses. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 103–151. https://doi.org/10.1007/978-3-642-35037-5_3.
Hammad, H.M., Khaliq, A., Abbas, F., Farhad, W., Fahad, S., Aslam, M., Shah, G.M., Nasim, W., Mubeen, M., Bakhat, H.F., 2020. Comparative effects of organic and inorganic fertilizers on soil organic carbon and wheat productivity under arid region. Commun. Soil Sci. Plant Anal. 51, 1406–1422. https://doi.org/10.1080/00103624.2020.1763385.
Herrera Huerta, J., Muñoz Alvear, E., Montalba Navarro, R., 2012. Evaluation of two production methods of Chilean wheat by life cycle assessment (LCA). IDESIA 30, 101–110. https://doi.org/10.4067/S0718-34292012000200013.
Holka, M., 2016. Life cycle assessment (lca) of winter wheat in an intensive crop production system in Wielkopolska region (Poland). Appl. Ecol. Environ. Res. 14, 535–545. https://doi.org/10.15666/aeer/1403_535545.
Holka, M., Bieńkowski, J., 2020. Assessment of environmental burdens of winter wheat production in different agrotechnical systems. Agronomy 10, 1303. https://doi.org/10.3390/agronomy10091303.
Ingrao, C., Licciardello, F., Pecorino, B., Muratore, G., Zerbo, A., Messineo, A., 2018. Energy and environmental assessment of a traditional durum-wheat bread. J. Clean. Prod. 171, 1494–1509. https://doi.org/10.1016/j.jclepro.2017.09.283.
International Organization for Standardization, 2006a. ISO 14040:2006 + A1:2020 - Environmental Management – Life Cycle Assessment – Principles and Framework. ISO.
International Organization for Standardization, 2006b. ISO 14044:2006 + A2:2020 - Environmental Management – Life Cycle Assessment – Requirements and Guidelines. ISO.
International Organization for Standardization, 2022. ISO/TS 14074:2022 – Environmental Management – Life Cycle Assessment – Principles, Requirements and Guidelines for Normalization, Weighting and Interpretation. ISO.
Iocola, I., Colombo, L., Dara Guccione, G., De Vita, P., Palumbo, M., Ritunnano, V., Sciacca, F., Virzì, N., Canali, S., 2021. A multi-criteria qualitative tool for the sustainability assessment of organic durum wheat-based farming systems designed through a participative process. Ital. J. Agron. 16, 1785. https://doi.org/10.4081/ija.2021.1785.
Istat, 2025. Istituto nazionale di statistica. https://www.istat.it/ (last accessed April 09.
Jekayinfa, S.O., Olaniran, J.A., Jaiyeoba, K.F., Olujide, O.S., 2015. Life cycle assessment of wheat production and processing system. Lautech Journal of Engineering and Technology 9, 79–86.
Jiang, Z., Zheng, H., Xing, B., 2021. Environmental life cycle assessment of wheat production using chemical fertilizer, manure compost, and biochar-amended manure compost strategies. Sci. Total Environ. 760, 143342. https://doi.org/10.1016/j.scitotenv.2020.143342.
Kazlauskas, M., Bručienė, I., Savickas, D., Naujokienė, V., Buragienė, S., Steponavičius, D., Romaneckas, K., Šarauskis, E., 2023. Life cycle assessment of winter wheat production using precision and conventional seeding technologies. Sustainability 15, 14376. https://doi.org/10.3390/su151914376.
Kheiralipour, K., Brandão, M., Holka, M., Choryński, A., 2024. A review of environmental impacts of wheat production in different agrotechnical systems. Resources 13, 93. https://doi.org/10.3390/resources13070093.
Khoshnevisan, B., Rafiee, S., Omid, M., Mousazadeh, H., Clark, S., 2014. Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. Journal of Cleaner Production, Towards eco-efficient agriculture and food systems: Selected papers from the Life Cycle Assessment (LCA) Food Conference, 2012, in Saint Malo, France 73, 183–192. https://doi.org/10.1016/j.jclepro.2013.09.057.
Liu, S., 2023. Towards a sustainable agriculture: achievements and challenges of sustainable development goal indicator 2.4.1. Global Food Secur. 37, 100694. https://doi.org/10.1016/j.gfs.2023.100694.
Liu, Y., Villalba, G., Ayres, R.U., Schroder, H., 2008. Global phosphorus flows and environmental impacts from a consumption perspective. J. Ind. Ecol. 12, 229–247. https://doi.org/10.1111/j.1530-9290.2008.00025.x.
Margni, M., Rossier, D., Crettaz, P., Jolliet, O., 2002. Life cycle impact assessment of pesticides on human health and ecosystems. Agric. Ecosyst. Environ. 93, 379–392. https://doi.org/10.1016/S0167-8809(01)00336-X.
Marraccini, E., Silvestri, N., Ingram, J., 2024. Co-designing innovative cropping systems with stakeholders. Ital. J. Agron. 18, 2213. https://doi.org/10.4081/ija.2023.2213.
Meier, M.S., Stoessel, F., Jungbluth, N., Juraske, R., Schader, C., Stolze, M., 2015. Environmental impacts of organic and conventional agricultural products – are the differences captured by life cycle assessment? J. Environ. Manag. 149, 193–208. https://doi.org/10.1016/j.jenvman.2014.10.006.
Update on scientific findings on the interactions between agriculture, food systems and climate change. In: Milne, E., Cerri, C.E., Schiettecatte, L.-S., Bernoux, M. (Eds.), 2025. Environment and Natural Resources Management Working Paper No. 110. FAO, Rome. https://doi.org/10.4060/cd6901en.
Mukosha, C.E., Moudrý, J., Lacko-Bartošová, M., Lacko-Bartošová, L., Eze, F.O., Neugschwandtner, R.W., Amirahmadi, E., Lehejček, J., Bernas, J., 2023. The effect of cropping systems on environmental impact associated with winter wheat production - an LCA "Cradle to Farm Gate" approach. Agriculture 13, 2068. https://doi.org/10.3390/agriculture13112068.
Mulimbi, W., Nalley, L.L., Strauss, J., Ala, -Kokko Kristiina, 2023. Economic and environmental comparison of conventional and conservation agriculture in South African wheat production. Agrekon 62, 133–151. https://doi.org/10.1080/03031853.2023.2169481.
Nemecek, T., Kägi, T., Blaser, S., 2007. Life cycle inventories of agricultural production systems. Final report ecoinvent v2. 0 No 15, 1–360.
Pourmehdi, K., Kheiralipour, K., 2023. Compression of input to total output index and environmental impacts of dryland and irrigated wheat production systems. Ecol. Indic. 148, 110048. https://doi.org/10.1016/j.ecolind.2023.110048.
Prado, V., Wender, B.A., Seager, T.P., 2017. Interpretation of comparative LCAs: external normalization and a method of mutual differences. Int. J. Life Cycle Assess. 22, 2018–2029. https://doi.org/10.1007/s11367-017-1281-3.
Shrestha, P., Karim, R.A., Sieverding, H.L., Archer, D.W., Kumar, S., Nleya, T., Graham, C.J., Stone, J.J., 2020. Life cycle assessment of wheat production and wheat-based crop rotations. J. Environ. Qual. 49, 1515–1529. https://doi.org/10.1002/jeq2.20158.
Sinab Sistema di informazione nazionale sull'agricoltura biologica. https://sinab.it/ (last accessed April 09, 2025).
Sumberg, J., Giller, K.E., 2022. What is 'conventional' agriculture? Global Food Secur. 32, 100617. https://doi.org/10.1016/j.gfs.2022.100617.
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. Prod. 197, 195–207. https://doi.org/10.1016/j.jclepro.2018.06.173.
Tedone, L., Ali, S.A., Mastro, G.D., Tedone, L., Ali, S.A., Mastro, G.D., 2017. Optimization of nitrogen in durum wheat in the mediterranean climate: the agronomical aspect and greenhouse gas (GHG) emissions. In: Nitrogen in Agriculture - Updates. IntechOpen. https://doi.org/10.5772/intechopen.70195.
Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677. https://doi.org/10.1038/nature01014.
Tudor, V.C., Stoicea, P., Chiurciu, I.A., Soare, E., Iorga, A.M., Dinu, T.A., David, L., Micu, M.M., Smedescu, D.I., Dumitru, E.A., 2023. The use of fertilizers and pesticides in wheat production in the main European countries. Sustainability 15, 3038. https://doi.org/10.3390/su15043038.
Van Stappen, F., Loriers, A., Mathot, M., Planchon, V., Stilmant, D., Debode, F., 2015. Organic versus conventional farming: the case of wheat production in Wallonia (Belgium). Agriculture and Agricultural Science Procedia, Farm Machinery and Processes Management in Sustainable Agriculture, 7th International Scientific Symposium 7, 272–279. https://doi.org/10.1016/j.aaspro.2015.12.047.
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.
White, P., Carty, M., 2010. Reducing bias through process inventory dataset normalization. Int. J. Life Cycle Assess. 15, 994–1013. https://doi.org/10.1007/s11367-010-0215-0.
Wilbois, K.P., Schmidt, J.E., 2019. Reframing the debate surrounding the yield gap between organic and conventional farming. Agronomy 9, 82. https://doi.org/10.3390/agronomy9020082.
Zingale, S., Guarnaccia, P., Matarazzo, A., Lagioia, G., Ingrao, C., 2022a. A systematic literature review of life cycle assessments in the durum wheat sector. Sci. Total Environ. 844, 157230.
Zingale, S., Guarnaccia, P., Timpanaro, G., Scuderi, A., Matarazzo, A., Bacenetti, J., Ingrao, C., 2022b. Environmental life cycle assessment for improved management of agri-food companies: the case of organic whole-grain durum wheat pasta in sicily. Int. J. Life Cycle Assess. 27, 205–226. https://doi.org/10.1007/s11367-021-02016-7.
Zingale, S., Ingrao, C., Reguant-Closa, A., et al., 2024. A multifunctional life cycle assessment of durum wheat cropping systems. Agron. Sustain. Dev. 44, 45. https://doi.org/10.1007/s13593-024-00982-4.