Environmental and Climate Technologies
2025, vol. 29, no. 1, pp. 1019–1031
https://doi.org/10.2478/rtuect-2025-0068
https://content.sciendo.com

Life Cycle Inventory of Soft Wheat in Central Italy: A Primary Data-Based Study

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Received 11.04.2025; accepted 29.10.2025

***Abstract* – Wheat is a key global crop, providing about 20 % of dietary calories and protein in human diet. Italy produces 6.5 million ton annually on 540,000 hectares, ranking among the top 15 global producers. The aim of this study is to present a Life Cycle Inventory (LCI) of the soft wheat supply chain in central Italy, aligned with 14044:2006, using primary data provided by three major Umbrian farms (central Italy) as a part of the supply chain of an important Italian bakery products industry (Colussi SpA). These farms are large enough to be considered representative of the industrial wheat production in central Italy. Among the various stages of soft wheat production analyzed, the investigated system puts an emphasis on the protection against fungal diseases and the use of pesticides, as this phase involves particularly critical points due to process variability. The data collected for the LCI refers to 1 ton of product, and all the stages from raw materials production to seed harvesting were considered. Precise estimations of fuel consumption were performed by considering the specific power requirements of different soil operations. Furthermore, the incorporation of stubble into the soil, a common practice in the region, was partially included in the nitrogen emission calculations. While seed treatment and carbon input to the soil could not be accounted for, due to data unavailability, the study lays the groundwork for future integration of these elements by identifying suitable methodologies and data gaps. This study provides one of the few regionalized inventories available for soft wheat production, addressing a significant gap in the current literature, which often relies on secondary data due to the scarcity of primary datasets. A key contribution of this work is the integration of previously unavailable data, especially concerning emissions from pesticides and fertilizers – data typically absent from databases and often overlooked in LCA studies despite their relevance. Overall, this regionalized inventory contributes to the development of more accurate and context-specific environmental assessments of soft wheat production. It can serve as a reference for future studies in comparable agro-climatic areas and supports the improvement of sustainability strategies in cereal farming systems.**

***Keywords* – Life Cycle Assessment; environmental impact; soft wheat; LCI.**

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1. INTRODUCTION

Soft wheat (*Triticum aestivum* L. *subsp. aestivum*) is the most widely cultivated cereal worldwide [1]. This makes it a fundamental food source for human nutrition, providing a substantial share of caloric intake [2] and playing a crucial role in food security.

According to 2021 estimates, a total of 1.7 million hectares was dedicated to this crop in Italy [3], with 41 % of the production used for human consumption and 35 % allocated to animal feed [4], the remaining 24 % is destined to seed production, storage, and biofuel manufacturing. As a result, Italy ranks as the twentieth largest producer of soft wheat in the world, with a total production of 6.89 million ton in 2023, showing an upward trend [5]. Despite its widespread cultivation, domestic wheat production remains insufficient to meet national demand, covering only 60 % of consumption [6].

Wheat cultivation has significant implications not only for social and economic factors but also for environmental concerns, particularly in relation to climate change, water use, and land use [7]. For this reason, public authorities have developed strategies such as the "Farm to Fork" program, which is part of the European Green Deal, with the aim of making the European production system a global benchmark for sustainability [8]. Given its extensive global cultivation, making it the crop covering the largest cultivated area worldwide [9], its environmental impact is substantial. Wheat cultivation contributes to 24 % of the global greenhouse gas (GHG) emissions attributed to agriculture [10], this sector alone accounts for 30 % of global anthropogenic emissions, according to the IPCC [11]. These emissions result from the use of agricultural inputs and machinery, whose environmental impact varies depending on the level of technological advancement [12].

In this context, the adoption of innovative tools is necessary to assess the environmental impact of agricultural production, increase awareness of its footprint and identify the most impactful stages to enable targeted improvements. The Life Cycle Assessment (LCA) methodology provides a standardized framework for analyzing the production process of a product across its entire life cycle, enabling comparisons between different production systems [9]. The application of LCA to agriculture is promising and expanding, yet it still faces significant limitations due to the complexity and variability of agricultural systems [13]. In fact, several agricultural factors are challenging to synthesize as required for LCA application, including the use of pesticides and their impact on human and environmental toxicity [14].

Existing models aim to estimate the environmental impact of pesticide use in agriculture, but the most commonly used ones are based on secondary data instead of direct measurements. For this reason, many of the difficulties in applying the LCA method to agriculture are found in the inventory phase. In fact, the measurement of specific elements is often complex. This includes some outputs, such as waste, but also some inputs like electricity consumption, which may be unavailable due to technical reasons.

Even more complex is the calculation of emissions, especially those caused by the use of fertilizers and pesticides, because it is very difficult to determine with certainty which environmental compartment a substance ends up in. For this purpose, models or tools exist that estimate emissions into specific environmental compartments based on data that are easier to find. However, these models and tools are not always suitable for the conditions of a specific study, and it is necessary to do detailed research to find the most appropriate one for each case.

This study fits into this context, offering an inventory based on data collected from three large farms that are part of the Colussi supply chain. Colussi is one of the main food companies in Italy, producing pasta, baked goods, and confectionery products. The selected farms are large enough to be considered representative of industrial soft wheat production in Central Italy. In fact, the farms cover areas respectively of 1900 ha, 617 ha, and 328 ha, compared to the national average of 14.2 ha per farm [3].

The aim of this study is to quantify the inputs and outputs of the soft wheat production process while minimizing uncertainties. Accuracy was improved by using primary data collected from real farms located in the Umbria region over a five-year period. The resulting inventory is therefore representative of Central Italy and is suitable for use in an LCA study to calculate the overall environmental impact of similar production systems.

Specifically, all the steps required for the assessment phase have been completed: the goal and scope were defined, the functional unit and system boundaries were established, and all system inputs and outputs were recorded, including emissions from fertilizers and pesticides.

This approach allows not only the quantification of environmental and human health impacts but also offers a representative methodology for future research on the environmental impact of the cereal supply chain in Central Italy, with a perspective that goes beyond the academic field.

2. Materials and Methods

This study presents and describes the inventory analysis phase of soft wheat production, using as a case study three farms that are part of the Colussi supply chain and representative of central Italy production. These farms are large enough to be considered representative of the industrial wheat production in central Italy Moreover, their yields are close to the national average for soft wheat (6.02 t/ha and 5.75 t/ha, respectively). In addition, the production techniques used in the Colussi supply chain follow national guidelines, based on the Integrated Production Protocol [15], which has been mandatory since 2009 and is updated every year.

The inventory developed will be integrated into a complete Life Cycle Assessment (LCA) to be conducted subsequently, in accordance with the guidelines set out in ISO 14040 [16] and ISO 14044 [17] standards, with the aim of evaluating the environmental impact of the entire production process.

The data presented in the following chapter, in addition to being collected according to the previously mentioned guidelines, were processed using a weighted average based on the size of the considered fields. Afterwards, the standard deviation was calculated in order to assess data variability.

2.1. Goal and Scope

The goal of this study is to conduct an inventory analysis that follows the sustainable production process of soft wheat in Italy, from cradle to grave. Considering the variability of the Italian territory, production processes may not be the same across the country. In this case, a representative case study of the Umbria region, located in central Italy, was examined. Data collection covered the years from 2019 to 2024, and for the inventory analysis, all inputs and outputs of the production process were considered and quantified. The defined goal is to develop a structured inventory for a future LCA study, which can also be considered representative of common wheat production in central Italy. In this way, the aim is to provide data on this agricultural process and its related emissions, which are usually difficult to obtain.

2.2. Functional Unit

The definition of the functional unit is a fundamental step, as it provides the reference for normalizing all data in the analysis [18]. In the application of LCA to the agricultural sector, the functional unit can change due to the multifunctionality of the sector, making it possible to use different units such as product mass, cultivated area, or gross profit [19]. For this study, the chosen functional unit is product mass (1 ton), as already applied in previous similar studies [20]–[21]. This choice also facilitates the integration with potential further studies on industrial processes that include wheat production.

2.3. System Boundaries

The system boundaries were defined based on sustainable agronomic wheat cultivation techniques, determined by the Integrated Pest Management (IPM) regulations of the Umbria region. Data were directly collected from three farms all located in Umbria. This approach not only establishes the quantitative system boundaries but also the geographical scope [23]. The reference period covered five years, from the wheat season 2019/2020 to the 2023/2024 one, including five production cycles from sowing to harvesting.

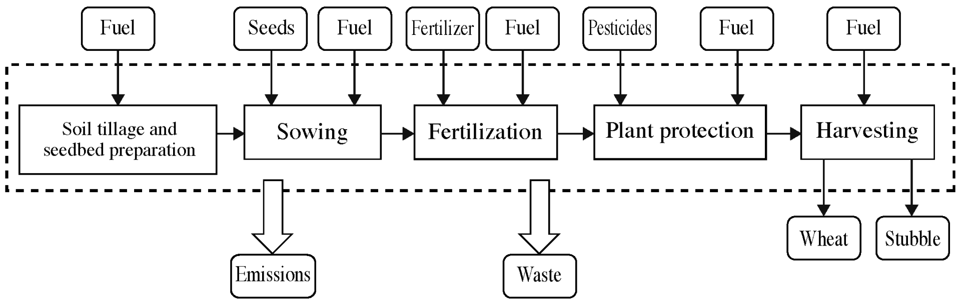

Fig. 1 system boundaries.

As shown in Fig. 1, the preliminary phases included within the system boundaries are: seedbed preparation, seed production, pesticides and fertilizers production, fuel use, transportation, and the entire production phase. The agronomic processes considered in crop growth include sowing, the application of plant protection products and fertilizers, and harvesting. The main outputs are the final product, stubble, and other waste materials. In cases where primary data were not available, values were estimated or obtained from the literature.

3. LCI RESULTS

The results section presents the inventory data according to the provided structure suggested by [24] for safflower, adapted to soft wheat production.

3.1. Land

Data was collected from three operational farms situated in the province of Perugia, all of which were part of the Colussi supply chain. These farms were selected to ensure a representative sample of typical agricultural practices within the region. For each farm, one representative plot of land was selected from the various fields, based on factors such as crop type, soil characteristics, and management practices, to be used for detailed soil analysis. From each selected plot, a sample of one kg of soil was collected using a coring method. The results obtained from the primary data collection are summarized in Fig. 2, which shows the percentages of soil composition (clay, sand, and silt). The soil organic matter (SOM) content, expressed as g/kg, was 1.99 for farm 1, 1.42 for farm 2 and 1.45 for farm 3. The SOM represents part of the biochemical composition of the soil. All selected plots were located on land already designated for agricultural use and managed under integrated crop rotation systems [24], ensuring the reliability and relevance of the findings to ongoing farming operations. Site-specific soil data are highly important, as they provide the foundation for applying models and methodologies that improve the accuracy and credibility of a study. However, obtaining such detailed soil data is not always feasible due to limitations in resources, such as the ability to collect samples or conduct laboratory analyses. For this reason, making available soil data collected from various locations within the Province of Perugia not only increases the value of the present study, but also provides useful information for future research that may derive from this inventory.

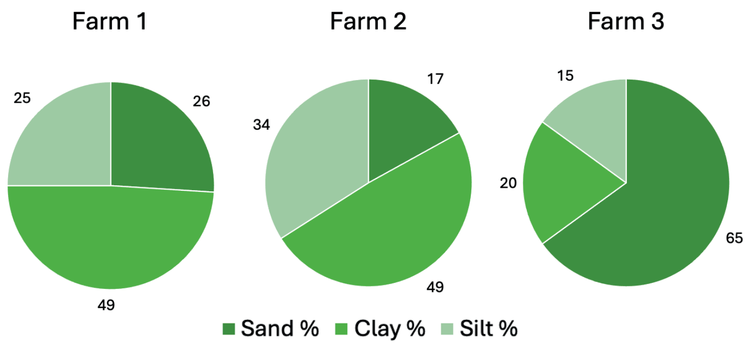

Fig. 2 Comparative soil texture composition across the considered farms.

3.2. Yield

The average yield of soft wheat in Italy is approximately 6.02 ton per hectare [3], compared to a global average of 3.5 t/ha [25], positioning the country above the global average in terms of productivity. This high yield is primarily due to the Italian favorable pedoclimatic conditions, which provide an ideal environment for soft wheat cultivation. Additionally, farmers benefit from extensive agronomic expertise and a deep understanding of best practices tailored to local conditions, including soil tillage, fertilization, irrigation, and pest management strategies.

The farms selected for this study are among the most experienced and advanced in the Umbria region. These farms have a long-standing tradition in cereal production which in the case of the youngest farm dates back 50 years, while the other two boast records going back two centuries, having undergone numerous changes before taking on their current form in the first half of the 20th century, that have consistently demonstrated a strong commitment to both agricultural innovation and environmental sustainability. In particular, they stand out for their high level of digitalization, including the use of precision agriculture technologies such as GPS-guided machinery, remote sensing, and digital farm management platforms. This integration of technological tools allows for more efficient resource use, improved monitoring of crop conditions, and enhanced decision-making processes.

Their combination of traditional knowledge and modern innovation makes them ideal case studies for assessing the potential of sustainable and efficient soft wheat production in central Italy. The detailed primary data collected from these farms, which form the basis for subsequent analysis, are presented in Table 2.

TABLE 1. SOFT WHEAT YIELD (T/HA) FOR THE THREE STUDIED FARMS IN UMBRIA (2020–2024) AND STANDARD DEVIATIONS (SD)

Farm	2020		2021		2022		2023		2024	
	Yield, t/ha	**SD**	**Yield, t/ha**	**SD**	**Yield, t/ha**	**SD**	**Yield, t/ha**	**SD**	**Yield, t/ha**	**SD**
1	5.70	0.22	4.69	0.19	4.70	0.17	4.95	0.14	5.74	0.32
2	6.49	N.A.	8.00	0.18	6.93	0.10	7.08	0.16	8.09	0.12
3	8.42	N.A.	4.01	N.A.	3.27	0.11	4.58	0.04	6.70	N.A.

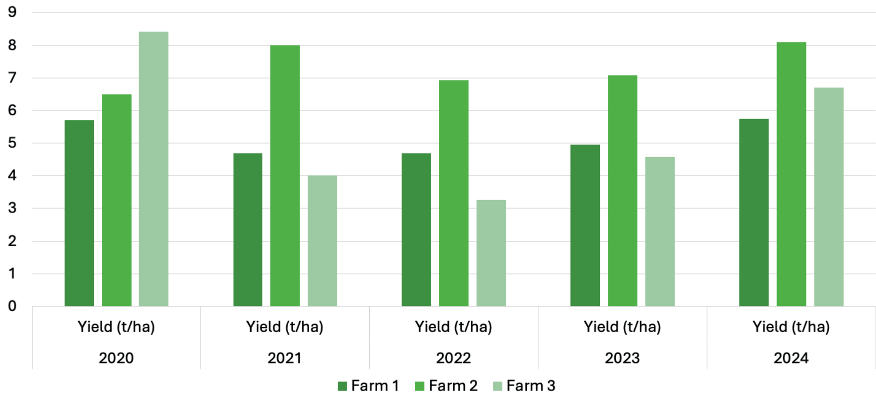

Fig. 3. Annual soft wheat yields (t/ha) recorded at the three farms selected for the case study in Umbria (2020–2024).

3.3. Materials

3.3.1. Seeds

The seeding rate of soft wheat is influenced by numerous variables, which collectively make it difficult to define an average seeding density. Among the factors that determine this value is the choice of the cultivar, which, as stated by, Lindsey *et al*, significantly impacts the optimal seeding density [27]. Weed management also affects the seeding density (SD), sometimes being used as a tool for weed control [27]. Another factor is the seeding technology, which can be crucial for optimizing the process [28], [29]. In the case of the farms selected for this study, the primary data collected indicate that the five-year average seeding density was 48.17 kg/t (SD 4.68). This value was obtained by calculating a weighted average (based on the size of the plots) using the seeding density data provided by the farms for the five years covered by the study, in order to ensure that the final value reflects actual field conditions and operational variability across the study area.

3.3.2. Fertilizers

The amino acid composition of wheat is essential for its nutritional quality [29], and protein development is highly dependent on fertilization.

This agricultural phase is particularly variable, as it depends on factors such as crop rotation, the wheat cultivar used, and the agronomic techniques employed [30]. The substances that need to be applied during the plant growth process are nitrogen (N), phosphorus (P), and potassium (K), and the dosage of these three elements is strongly interdependent, particularly with nitrogen [31]. The main issue with nitrogen fertilizers is that are susceptible to leaching, which consequently leads to water pollution, eutrophication, biodiversity loss, human toxicity, and ecotoxicity [32]. For these reasons, it is important to optimize fertilizers' use as much as possible and make it as efficient as possible. The farms involved in the study used different methods for nitrogen fertilization, varying both the dosage across different fields and the product chosen. Owing to the specific soil characteristics, potassium fertilization was deemed unnecessary and was substituted with sulfur-based fertilization. Most of them primarily applied nitrogen fertilizers in pure form, such as urea and ammonium nitrate, but over the years, there has been a shift toward slow-release formulations. Nevertheless, primary data were collected on the commercial fertilizer formulations used by the farms in the case study (quantity per hectare and composition). From this information, it was possible to identify the specific percentages of the main ingredients for each field, namely: ammonium nitrate, urea, P_2O_5, and SO_3. Then, an average per hectare of these active substances used by the farms over the five years covered by the study was calculated. These values are shown in Table 3.

TABLE 2. AVERAGE FERTILIZER INPUT PER TON OF PRODUCT: AMMONIUM NITRATE, UREA, SO_3, P_2O_5 (KG/T) 2020–2024 AND STANDARD DEVIATION (SD)

Ammonium nitrate		**Urea**		**SO_3**		**P_2O_5**	
kg/t	**SD**	**kg/t**	**SD**	**kg/t**	**SD**	**kg/t**	**SD**
5.07	6.89	19.47	6.46	3.73	6.13	3.68	4.90

3.3.3. Plant Protection

Plant protection refers to all treatments aimed at combating weeds, pathogens, and pests that could damage production both qualitatively and quantitatively.

The applications carried out were mostly post-emergence, except for the herbicide treatment applied by Farm 3 in 2023, which was carried out in pre-emergence.

The pesticides selected by the three farms involved in the study are suitable for the main threats encountered in the areas where these farms are located. Among these threats, fungal diseases such as fusarium head blight (*Fusarium* spp.) and rusts (*Puccinia* spp.) should be included, while the main weed species include *Lolium rigidum*, *Avena fatua*, and *Papaver rhoeas.* The application timing of plant protection products was also determined based on the development stages of the previously mentioned diseases, in order to make their use more efficient. The use of these products complies with the regional integrated pest management guidelines to ensure sustainable use. Given the extensive number of the applied pesticides recorded, a cut-off criterion was applied in accordance with LCA methodology to improve data manageability and focus on the most impactful contributors. Specifically, only those products used in at least 1 % of the total applications across the three pesticide categories, i.e. herbicides, fungicides, and insecticides, were included in the inventory analysis. Products falling below this threshold were excluded on the basis of their negligible contribution to the overall environmental impact. Among these, the following active substances were identified: florasulam, cloquintocet-mexyl, mesosulfuron-methyl, iodosulfuron-methyl-sodium, mefenpyr-diethyl, tribenuron-methyl, iodosulfuron-methyl-sodium, mefenpyr-diethyl, halauxifen-methyl, isopyrazam, and tetraconazole.

Table 3 shows the rates and the application areas of the pesticides used by the farms in the case study between 2020 and 2024 obtained like primary data.

TABLE 3. AVERAGE PESTICIDE INPUT PER HECTARE: HERBICIDES, FUNGICIDES, INSECTICIDES 2020–2024 AND STANDARD DEVIATION (SD)

Herbicides		
Acrive ingredient	**Rate, kg/t**	**SD**
Clopyralid	1.59E-03	4.68E-03
Pinoxaden	3.44E-03	1.71E-03
Clodinafop-propargyl	2.95E-03	1.55E-03
Fluroxypyr	9.51E-03	1.15E-02
Sodium lauryl ether sulfate	7.45E-03	1.66E-02
Thifensulfuron-methyl	1.13E-03	1.76E-03
Tritosulfuron	3.28E-03	3.16E-03
Glyphosate	3.93E-02	1.09E-01
Diclorprop-P	9.19E-03	2.33E-02
MCPA	4.13E-03	1.23E-02
Mecoprop-P	3.86E-03	6.81E-02
Chlorotoluron	4.38E-03	2.75E-02
Fungicides		
Acrive ingredient	**Rate, kg/t**	**SD**
Fluxapyroxad	6.27E-03	5.90E-03
Pyraclostrobin	1.78E-02	1.42E-02
Prothioconazole	7.25E-03	9.52E-03
Bixafen	1.71E-03	4.11E-03
Metconazole	5.15E-03	7.02E-03
Benzovindiflupyr	1.34E-03	3.71E-03
Prochloraz	1.37E-03	5.54E-03
Tebuconazole	1.19E-03	4.89E-03
Mefentrifluconazole	2.42E-03	5.90E-03
Insetticides		
Active ingredient	**Rate, kg/t**	**SD**
Tau-fluvalinate	1.39E-03	1.61E-01

All pesticides were used after being diluted in water, with an average consumption of 74.8 L/t (SD 46.93).

3.4. Crop Residues

Wheat crop residues consist of the dry stem of the plant after the removal of the seed and husk [33], [35], providing an additional source of income for farmers when they sell it for animal feed.

Another possible use of wheat stubble is burial, which, when done properly, contributes to the addition of nitrogen and organic matter to the soil [34].

From the data collected for this study, it emerged that 63.5 % of the stubble was removed and sold, while the remaining 36.5 % was buried. These percentages were obtained from primary data, which, however, were not available for all hectares and all years. Consequently, when data were missing, the average value from the other plots was used.

3.5. Fuel Consumption

Agricultural machinery, during the wheat production process, is used in various stages, each with a different fuel consumption depending on the power required by the operation. However, for the LCA, it is crucial to accurately account for fuel consumption, as it is one of the most impactful steps [35].

Primary data was not available for all agricultural operations and all the farms involved, so an average was calculated using the available ones. The agricultural operations considered were grouped into the following categories: soil tillage, seeding, fertilization, plant protection, and harvesting. The average consumption in L/ha was then calculated, as shown in Table 4. One noteworthy value is the number of operations related to sowing, which is lower than 1. This is due to the use of combined sowing in some fields, where impacts were distributed between sowing and seedbed preparation.

TABLE 4. NUMBER OF MECHANICAL OPERATIONS AND FUEL CONSUMPTION FOR DIFFERENT FIELD PROCESSES AND STANDARD DEVIATION (SD)

Mechanical operations			
Type of process	**Number of operations**	**Fuel, L/t**	**SD**
Soil tillage and seedbed preparation	2.00	11.18	1.30
Sowing	0.80	3.43	0.66
Fertilization	3.50	1.20	0.12
Plant protection	1.82	1.45	0.07
Harvesting	1.00	4.32	1.00

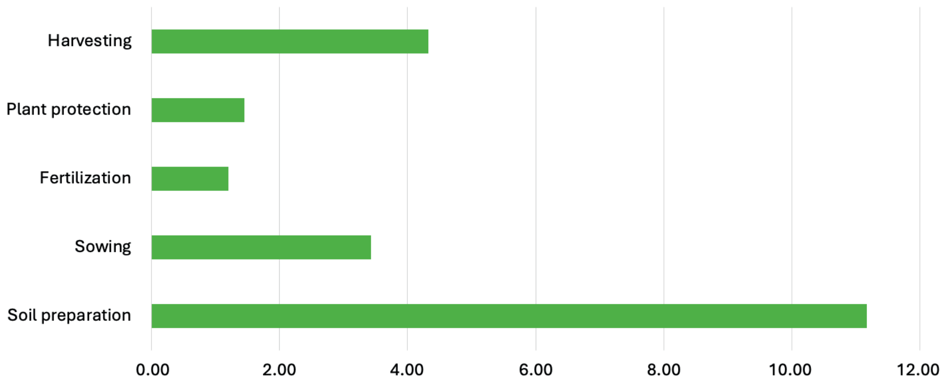

Fig. 4. Fuel consumption (L/t) per field process.

3.6. Direct Emissions

In the present study, emissions resulting from the use of pesticides and fertilizers were considered. These emissions depend on various factors, such as soil type and climatic conditions.

For pesticides, the estimation was based on the assumption made by Margni *et al.* [37] which was later applied in several studies, including [21] and [20]. According to this approach, 85 % of emissions are directed toward the soil, while 10 % are released into the air. Only the remaining 5 % is absorbed by the plant. To calculate the emissions in the environmental compartments of soil and air, the results from paragraph 3.3.3 were used. This section provides the amount of active ingredient used for plant protection, expressed in g/ha. Then, using a proportion, the percentage of emissions allocated to air and to soil was calculated. The results are shown in Table 5.

TABLE 5. ESTIMATED PESTICIDES EMISSION PER HECTARE FROM SOFT WHEAT PRODUCTION IN THE STUDIED FARMS (2020–2024)

Herbicides		
Acrive ingredient	**Soil emissions, kg/t**	**Air emissions, kg/t**
Clopyralid	1.35E-03	1.59E-04
Pinoxaden	2.92E-03	3.44E-04
Clodinafop-propargyl	2.51E-03	2.95E-04
Fluroxypyr	8.09E-03	9.51E-04
Sodium lauryl ether sulfate	6.33E-03	7.45E-04
Thifensulfuron-methyl	9.58E-04	1.13E-04
Tritosulfuron	2.79E-03	3.28E-04
Glyphosate	3.34E-02	3.93E-03
Diclorprop-P	7.81E-03	9.19E-04
MCPA	3.51E-03	4.13E-04
Mecoprop-P	3.28E-03	3.86E-04
Chlorotoluron	3.73E-03	4.38E-04
Fungicides		
Acrive ingredient	**Soil emissions, kg/t**	**Air emissions, kg/t**
Fluxapyroxad	5.33E-03	6.27E-04
Pyraclostrobin	1.51E-02	1.78E-03
Prothioconazole	6.16E-03	7.25E-04
Bixafen	1.45E-03	1.71E-04
Metconazole	4.37E-03	5.15E-04
Benzovindiflupyr	1.14E-03	1.34E-04
Prochloraz	1.17E-03	1.37E-04
Tebuconazole	1.01E-03	1.19E-04
Mefentrifluconazole	2.06E-03	2.42E-04
Insecticides		
Acrive ingredient	**Soil emissions, kg/t**	**Air emissions, kg/t**
Tau-Fluvalinate	1.18E-01	1.39E-04

Direct emissions from fertilizers are primarily associated with nitrous oxide emissions, which are particularly harmful to the environment.

In this case study, only synthetic fertilizers were used, and emissions were calculated for nitrogen-based products, specifically urea and ammonium nitrate and phosphoric-based products. For nitrogen emissions, the method applied follows the Berntrup *et al.* [38] guidelines, according to which total nitrogen emissions into the environment result to be 3.02 kg/t of NH_3 in the air and 0.03 kg/t of N_2O in the soil. The emissions of phosphorus were calculated according to method described [38], resulting in a value of 0.19 kg/t in the water. In this case, some data, such as the amount of synthetic fertilizer applied or the fate of the stubble, were collected and are therefore considered primary data. However, other information, such as the amount of stubble produced per hectare, was not available, so the local average value was used. Similarly, the amount of nitrogen present in the soil was not available for all plots, so an average was calculated using the available data, as the locations are adjacent and, therefore, comparable.

4. CONCLUSIONS

This study presents a comprehensive Life Cycle Inventory (LCI) of industrial soft wheat production in Italy, developed through the collection and analysis of primary data from farms located in the Umbria region. As such, it offers a regionalized and context-specific dataset that reflects real-world agricultural practices and can serve as a robust reference point for future Life Cycle Assessment (LCA) studies.

To date, few LCAs have specifically addressed industrial soft wheat production, often relying on secondary datasets due to the lack of direct measurements thus included in more consistent LCI. This reliance has limited the precision and relevance of environmental assessments. By contrast, this study utilizes detailed, farm-level primary data, thereby improving the specificity and reliability of the inventory and offering a significant contribution to the existing body of research. This will provide professionals with the tools to consider data related not only to the territory of Central Italy, but also to the agricultural practices typical of our country.

The standard deviation values obtained showed significantly elevated values in multiple instances. This reflects the intrinsic heterogeneity of agricultural practices, especially in our region, and the environmental conditions that vary from year to year. Such variability is common in LCA studies applied to agricultural systems. For this reason, the present study is particularly relevant, as it provides thoroughly collected data over a sufficiently long time period (5 years) and across a representative agricultural area.

A major gap in previous studies, namely, the lack of emissions data associated with pesticide and fertilizer use, was addressed here. These emissions are often excluded due to the absence of data in LCA databases, despite their critical role in determining the environmental footprint of agricultural systems. By incorporating modelled estimates based on established methodologies, this study helps bridge that gap and provides a complete picture of emissions.

Fuel consumption, another key contributor to the environmental impact of wheat production, was also analyzed in detail. Distinctions were made between operations such as soil tillage, which is highly energy-intensive (11.18 L/t), and less demanding activities like pesticide and fertilizer applications (1.45 and 1.2 L/t, respectively). These distinctions highlight the importance of accurately capturing operational variability in LCA studies.

The methodologies used to obtain these results were all derived from specific studies and were selected after verifying their applicability to this research. The verification process included checking for previous studies in which the same methodologies have been applied.

Additionally, the management of crop residues, a product of wheat cultivation, was partially considered. The incorporation of stubbles into the soil was included in the nitrogen emission calculations.

The primary contribution of this study lies in the generation of accurate and representative data on soft wheat production from a key agricultural region in Italy. The participating farms, due to their size, practices, and integration within the Colussi supply chain, provide a credible reflection of regional production dynamics. Moreover, more accurate estimates in environmental impact assessments not only give greater credibility to the study, but also provide companies with a useful tool to support eco-labelling schemes, obtain environmental certifications, and plan local strategies and agri-food policies.

Looking ahead, future studies could expand this work by incorporating data on seed treatment, including both the substances used and the processing stages, i.e. an area for which no reliable data was available in this study, and an extended LCA study could be performed. Furthermore, there is growing interest in including beneficial inputs in environmental assessments, such as carbon sequestration resulting from stubble incorporation and other sustainable practices. Developing methodologies to quantify such contributions would enhance the holistic evaluation of agricultural systems.

Acknowledgement

Claudia Camplone's PhD grant was funded by the National Recovery and Resilience Plan (NRRP) from the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU and by Colussi SpA.

References

[1] Zingale S., Guarnaccia P., Matarazzo A., Lagioia G., Ingrao C. Factors Affecting the Nutritional, Health, and Technological Quality of Durum Wheat for Pasta-Making: A Systematic Literature Review. *Plants* 2023:12(3):530. https://doi.org/10.3390/plants12030530

[2] Shiferaw B., Smale M., Braun H. J., Duveiller E., Reynolds M., Muricho G. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Secur* 2013:5(3):291–317. https://doi.org/10.1007/s12571-013-0263-y

[3] ISTAT. Report agricoltura, 2020.

[4] Alomari D. Z., Schierenbeck M., Alqudah A., Alqahtani M., Wagner S., Rolletschek H., Borisjuk L., Röder M. Wheat Grains as a Sustainable Source of Protein for Health. *Nutrients* 2023:15(20). https://doi.org/10.3390/nu15204398

[5] Food and Agriculture Organization of the United Nations (FAO). *FAOSTAT_data*, 2023.

[6] Amicarelli V., Lombardi M., Varese E., and Bux C. Material flow and economic cost analysis of the Italian artisan bread production before and during the Russia-Ukraine conflict. *Environ Impact Assess Rev* 2023:101. https://doi.org/10.1016/j.eiar.2023.107101

[7] FAO. Climate change, water and food security, 2011.

[8] Paolotti L., Corridoni F., Rocchi L., and Boggia A. Evaluating Environmental Sustainability of Pasta Production through the Method LCA. *Environmental and Climate Technologies* 2023:27(1):593–605. https://doi.org/10.2478/rtuect-2023-0044

[9] Falcone G., Stillitano T., Montemurro F., De Luca A. I., Gulisano G., Strano A. Environmental and economic assessment of sustainability in mediterranean wheat production. *Agronomy Research* 2019:17(1):60–76. https://doi.org/10.15159/AR.19.011

[10] IPCC. Final Report, *IPCC*, 2004.

[11] Luksta I., Pakere I., Vamža I., Liberova V., Blumberga D. Comparative Analysis of Agricultural Emissions Across European Countries. *Environmental and Climate Technologies* 2024:28(1):738–748. https://doi.org/10.2478/rtuect-2024-0057

[12] Ali S. A., Tedone L., and De Mastro G. Optimization of the environmental performance of rainfed durum wheat by adjusting the management practices. *J Clean Prod* 2015:87(1):105–118. https://doi.org/10.1016/j.jclepro.2014.09.029

[13] Lucas K. R. G., Caldarelli C.E., Ventura M. U., Tang L., Hayashi K., and Yoshikawa N. Mapping life cycle assessment (LCA) scientific research in agriculture: what do we still have to do? *Environ Syst Decis* 2025:45(1). https://doi.org/10.1007/s10669-024-09997-4

[14] Tang L., Hayashi K., Nagai T., and Inao K. Preciseness, rather than simplicity, is required to assess pesticide reduction strategies: Findings from rice production in Japan. *Science of the Total Environment* 2023:887. https://doi.org/10.1016/j.scitotenv.2023.163636
[15] Regione Umbria. Disciplinare di produzione integrata Umbria - Allegato B, *Regione Umbria,* 2024.
[16] ISO. Environmental management-Life cycle assessment-Principles and framework Management environmental, 2006.
[17] ISO. ISO 14044 Environmental Management-Life cycle assessment-Requirements and guidelines Management environmental, 2006.
[18] Weidema B., Wenzel H., Econet C. P., and Hansen K. The Product, Functional Unit and Reference Flows in LCA, 2004.
[19] Hayashi K., Gaillard G., Nemecek T., and Fal Reckenholz A. Life cycle assessment of agricultural production systems: current issues and future perspectives. 2006.
[20] Fantin V., Righi S., Rondini I., and Masoni P. Environmental assessment of wheat and maize production in an Italian farmers' cooperative. *J Clean Prod* 2017:140:631–643. https://doi.org/10.1016/j.jclepro.2016.06.136
[21] Schmidt Rivera X. C., Bacenetti J., Fusi A., and Niero M. The influence of fertiliser and pesticide emissions model on life cycle assessment of agricultural products: The case of Danish and Italian barley. *Science of the Total Environment* 2017:592:745–757. https://doi.org/10.1016/j.scitotenv.2016.11.183
[22] Verdi L., Marta A. D., Falconi F., Orlandini S., and Mancini M. Comparison between organic and conventional farming systems using Life Cycle Assessment (LCA): A case study with an ancient wheat variety. *European Journal of Agronomy* 2022:141. https://doi.org/10.1016/j.eja.2022.126638
[23] Yang Y. Toward a more accurate regionalized life cycle inventory. *J Clean Prod* 2016:112:308–315. https://doi.org/10.1016/j.jclepro.2015.08.091
[24] Rocchi L., Farneselli M., Paolotti L., Falcinelli B., Guiducci M., Boggia A. Life Cycle Inventory for Safflower Production in Southern Europe. *Environmental and Climate Technologies* 2022:26(1):862–870. https://doi.org/10.2478/rtuect-2022-0065
[25] Ball B. C., Bingham I., Rees R. M., Watson C.A., and Litterick A. The role of crop rotations in determining soil structure and crop growth conditions. *Canadian Journal of Soil Science* 2005:85(5). https://doi.org/10.4141/S04-078
[26] Zolotnytska Y., Kowalczyk S., Sobiecki R., Krupin V., Krzyżanowski J., Perkowska A., Żurakowska-Sawa J. Drivers of Global Wheat and Corn Price Dynamics: Implications for Sustainable Food Systems. *Sustainability* 2025:17(19):8581. https://doi.org/10.3390/su17198581
[27] Lindsey L. E., Goodwin A. W., Harrison S. K., and Paul P. A. Optimum seeding rate and stand assessment of soft red winter wheat. *Agron J* 2020:112(5):4069–4075. https://doi.org/10.1002/agj2.20303
[28] Cox W., Cherney J., and Sorrells M. Organic compared with conventional wheat had competitive yields during the early years of organic production in the northeast USA. *Agronomy* 2019:9(7):380. https://doi.org/10.3390/agronomy9070380
[29] Di Giuseppe E., Galdenzi G., D'Orazio M., and Di Perna C. Existing buildings retrofit through multi-objective optimization: a case-study. *TEMA, Technologies Engineering Materials Architecture* 2018:4(2). https://doi.org/10.30682/tema0402a
[30] Crista F. Influence of NPK Fertilizers Upon Winter wheat grain quality. *Research Journal of Agricultural science* 2012.
[31] Litke L., Gaile Z., and Ruža A. Effect of nitrogen fertilization on winter wheat yield and yield quality. *Agronomy Research* 2018:16(2):500–509. http://dx.doi.org/10.15159/ar.18.064
[32] Rawal N., Pande K. R., Shrestha R., and Vista S. P. Nutrient use efficiency (NUE) of wheat (Triticum aestivum L.) as affected by NPK fertilization. *PLoS One* 2022:17(1). https://doi.org/10.1371/journal.pone.0262771
[33] Huang P. Zhang J., Zhu A., Li X., Ma D., Xin X., Zhang C., Wu S., Garland G., Pereira E. Nitrate accumulation and leaching potential reduced by coupled water and nitrogen management in the Huang-Huai-Hai Plain. *Science of the Total Environment* 2018:610–611:1020–1028. https://doi.org/10.1016/j.scitotenv.2017.08.127
[34] Singh A., Singh N., Bishnoi N. R. Production of Cellulases, 2009.
[35] Murray T. D., Bruehl G. W. Compostion of wheat straw with Cephalosporium graminearum and implicationfot its decomposition in soil. *Phytopathol* 1983.
[36] Mamkagh A. M., Salim Al-Aani F., Alberto Ferreira Lagarinhos C. Effect of Tillage Speed, Depth, Ballast Weight and Tire Inflation Pressure on the Fuel Consumption of the Agricultural Tractor: A Review. *Journal of Engineering Research and Reports* 2018:3(2):46116. https://doi.org/10.9734/jerr/2018/v3i216871
[37] Margni M., Rossier D., Crettaz P., and Jolliet O. Life cycle impact assessment of pesticides on human health and ecosystems. *Agriculture, Ecosystems & Environment* 2002:93(1–3):379–392. https://doi.org/10.1016/S0167-8809(01)00336-X
[38] Brentrup F., Kiisters J., Lammel J., Kuhlmann H. LCA Methodology Nitrogen Emissions LCA Methodology Methods to Estimate On-Field Nitrogen Emissions from Crop Production as an Input to LCA Studies in the Agricultural Sector. *The International Journal of Life Cycle Assessment* 2000:5:349–357. https://doi.org/10.1007/BF02978670