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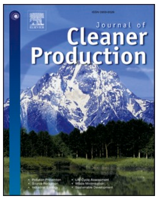

How can the environmental impacts of wheat cultivation and wheat flour production be reduced? A life cycle assessment of Brazilian wheat

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ABSTRACT

Wheat and wheat flour play a vital role in global food security. There is a knowledge gap regarding the environmental impacts associated with wheat cultivation and wheat flour production in subtropical and tropical environments. As one of the world's major grain producers, Brazil needs to identify and mitigate the environmental impacts of its agricultural products. This study aimed to (1) identify the environmental impacts of the Brazilian wheat cultivation and flour production system and (2) propose strategies to mitigate the environmental impacts. The study was conducted in Brazil's main wheat-producing region, assessing 61 farms in the wheat cultivation, grain transport, processing, and milling processes. Environmental impacts were calculated using SimaPro 9.5.0.2 with the Ecoinvent® v3.5 database. Wheat cultivation was the primary source of environmental impacts in Brazilian wheat flour production, contributing between 67% and 98% across the categories analysed. The carbon footprint of wheat cultivation was 0.50 kg CO_2eq kg wheat^{-1}, while wheat flour production ranged from 0.67 to 0.80 kg CO_2eq kg flour wheat^{-1}. Field emissions, particularly N_2O from urea, significantly impacted the global warming potential (GWP). The grain transport had a marginal environmental impact ($<1.5\%$), and the grain processing contributed minimally, while wheat milling had a higher impact on freshwater eutrophication potential (FEP). Replacing urea with calcium ammonium nitrate (CAN) and more productive wheat varieties reduced environmental impacts in the wheat cultivation process. The use of photovoltaic energy in grain processing and milling reduced industrial environmental impacts. Brazilian wheat flour proved to be environmentally competitive compared to production in other countries, especially in terms of carbon footprint, providing insights into wheat cultivation for subtropical and tropical environments.

1. Introduction

Food production has been reported as one of the principal causes of greenhouse gas (GHG) emissions, contributing significantly to climate change (Feng et al., 2023a). Moreover, crop cultivation and food production impact other environmental categories, such as ecotoxicity,

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freshwater use, eutrophication, and acidification (Rafiee et al., 2024). Considering the growth of global population, which may reach 10.2 billion by the end of the century (United Nations, 2024), there is a necessity to mitigate the environmental impact of products and make food production more sustainable. Understanding where and how environmental impacts occur throughout specific food supply chains is crucial for farmers, agri-food industry, and consumers to share responsibility in mitigating these effects (Poore and Nemecek, 2018).

Among the most consumed foods worldwide, grains provide, on average, a third of human dietary calories (Ibrahim et al., 2024). Grain production utilises a significant proportion of global natural resources, including 36% of productive land, 34% of freshwater, and 45% of total fertilisers used in agriculture, emitting, for example, around 36% of total GHGs from crop cultivation (Milani et al., 2024). Wheat is the second most produced grain in the world (784.91 million metric tons), after maize (1235.71 million metric tons), in the 2023/24 harvest (Statistica, 2024). Its derivatives, such as wheat flour, also have a significant impact on the global food chain (Câmara-Salim et al., 2020).

Given the urgency to mitigate the damage caused by human consumption, life cycle assessment (LCA), standardised by ISO 14040 (ISO - International Organization for Standardization, 2006a) and ISO 14044 (ISO - International Organization for Standardization, 2006b), has been used as a tool to estimate and identify the critical points of major environmental impacts caused by the production of goods and services (Feng et al., 2023a). LCA thus becomes a tool for reflection and decision-making on strategies to ensure sustainable production, including food production (Riedesel et al., 2022). The environmental footprint managed by ISO 14067 (ISO - International Organization for Standardization, 2018), for the Global Warming Potential (GWP) category, and ISO 14046 (ISO - International Organization for Standardization, 2014) for categories related to water use, toxicity, eutrophication and acidification assess the sustainability of production systems.

In a recent review on food commodities, no results were found for the environmental impact assessment of wheat and wheat flour produced in South America and, consequently, in Brazil, through LCA (Feng et al., 2023a). There is a knowledge gap regarding the environmental impacts caused by wheat cultivation and wheat flour production in subtropical and tropical environments. Brazil is one of the world's major grain producers, expected to produce 312.3 million tonnes in the 2023/24 harvest. Wheat production occurs on both large and small farms, with an average production between 2013 and 2023 of 6.6 million tonnes (Mt) (CONAB- Companhia Nacional de Abastecimento, 2024). Although production still does not meet the domestic demand of 12 million tonnes (Nóia Júnior et al., 2024). There is a diversity of initiatives to expand Brazilian wheat production, in areas where already cultivated others crops, to meet domestic demand and position Brazil as a global player. In this context, given the importance of Brazilian grain production, estimating the environmental impacts of wheat cultivation and flour production in Brazil through LCA will contribute to advancing scientific knowledge. There are still questions to be addressed, such as: (1) What are the environmental impacts of the current Brazilian wheat cultivation and flour production processes? (2) What strategies can be used to mitigate the environmental impact of wheat cultivation and flour production? This study aims to answer these questions by assessing the life cycle of Brazilian wheat cultivation and Brazilian wheat flour production. For this, we present the environmental impacts of four processes: (1) wheat cultivation, (2) grain transport, (3) grain processing, and (4) wheat milling. Subsequently, we present two strategies to reduce environmental impacts in the cultivation (replacement of urea with CAN and use of more productive varieties) and one strategy to reduce environmental impacts in grain processing and wheat milling (use of photovoltaic energy). Identifying critical points and suggesting applicable scenarios, our study will contribute to Brazilian wheat cultivation and Brazilian wheat flour production becoming more competitive and sustainable, providing insights into wheat cultivation for subtropical and tropical environments.

2. Material and methods

2.1. Study area

The study was conducted in Paraná state, Brazil's leading wheat-producing region (CONAB- Companhia Nacional de Abastecimento, 2024). A total of 61 farms, ranging from 7 to 697 ha, in the Southeast and Central-East mesoregions, covering 202,600 ha of wheat production (IBGE - Instituto Brasileiro de Geografia e Estatística, 2023), were surveyed to assess the life cycle of Brazilian wheat cultivation (Fig. 1, Annexes A and B, Supplementary Material _SM).

All 61 farms included in the study deliver their wheat to Moageira Irati, a mill that was established in 1949. This mill processes an average of 84,000 tonnes of wheat annually and produces approximately 63,000 tonnes of flour per year, based on the average of 2021, 2022, and 2023. The wheat undergoes a processing involving cleaning, drying, and storage before being milled into flour. The resulting wheat flour is then sold to the market in bulk or packaged in large bags.

2.2. Objectives, scope and functional unit

The main objective of this study was to assess the environmental impact of Brazilian wheat and wheat flour production. A life cycle assessment (LCA) was conducted to evaluate the environmental impacts of producing 1 kg of wheat grain and 1 kg of wheat flour, encompassing cultivation in large and small farms, transportation, processing, and milling (Fig. 2). The cradle-to-gate approach was adopted to each process, excluding post-mill stages such as storage, transportation, and distribution of wheat flour. Data were collected over three consecutive years (2021–2023).

2.3. Description of the systems

2.3.1. Wheat cultivation

Wheat rainfed cultivation in Brazil is concentrated mainly in the South, where 3.04 million hectares were sown in 2023, accounting for 88% of the national wheat area (CONAB- Companhia Nacional de Abastecimento, 2024). Irrigated wheat cultivation is still emerging in the Southeast and Central-West, it shows significant growth potential (Soares et al., 2023). Sowing typically occurs between April and June, benefiting from milder temperatures. Harvesting takes place 110–140 days after sowing, depending on the cultivar. The main cultivars include ORS Feroz, TBIO Ponteiro, TBIO Calibre, TBIO Audaz, TBIO Sonic, ORS Madre Pérola, and TBIO Tibagi.

All farms analysed practice no till and crop rotation, mainly with oats, corn, beans and soybeans. Soil acidity is mitigated through the application of dolomitic limestone, calcitic limestone, and gypsum, typically every three years, depending on farm-specific needs and crop intensity. Pre-emergence herbicides are applied 15 days before sowing. Sowing and the application of NPK-based fertilisers occur simultaneously. Seed rates range from 130 to 200 kg ha-1. Topdressing with nitrogen fertilisers is applied 30 days post-emergence. Fungicides, insecticides, and growth regulators are used as needed to manage pests, diseases, and lodging. The Ecoinvent® database was used to account for the environmental impacts of wheat cultivation processes (Annex C, SM). Wheat is harvested between late September and November using machines that separate grain from straw, which is returned to the field as organic residue. The grain is then transported to Moageira Irati.

2.3.2. Grain transportation

Grain is transported to Moageira Irati using two truck models: a 1980s Mercedes-Benz 1313, carrying 18 tons with an average fuel consumption of 3.77 km L^{-1}, and a 2012–2018 Volvo FH bitren, carrying 38 tons with an average fuel consumption of 2.3 km L^{-1}. The distance from farms to the mill ranges from 6.3 to 191 km. Fuel consumption was calculated based on round-trip distances during the

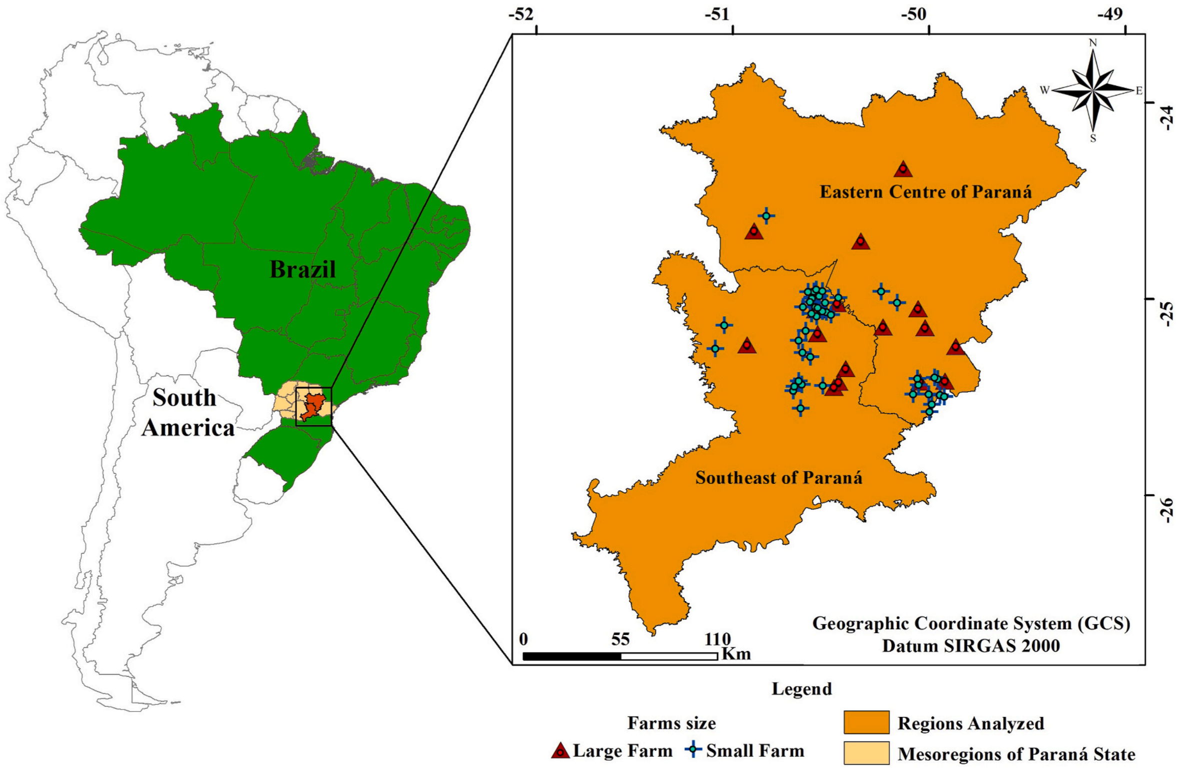

Fig. 1. Study area.

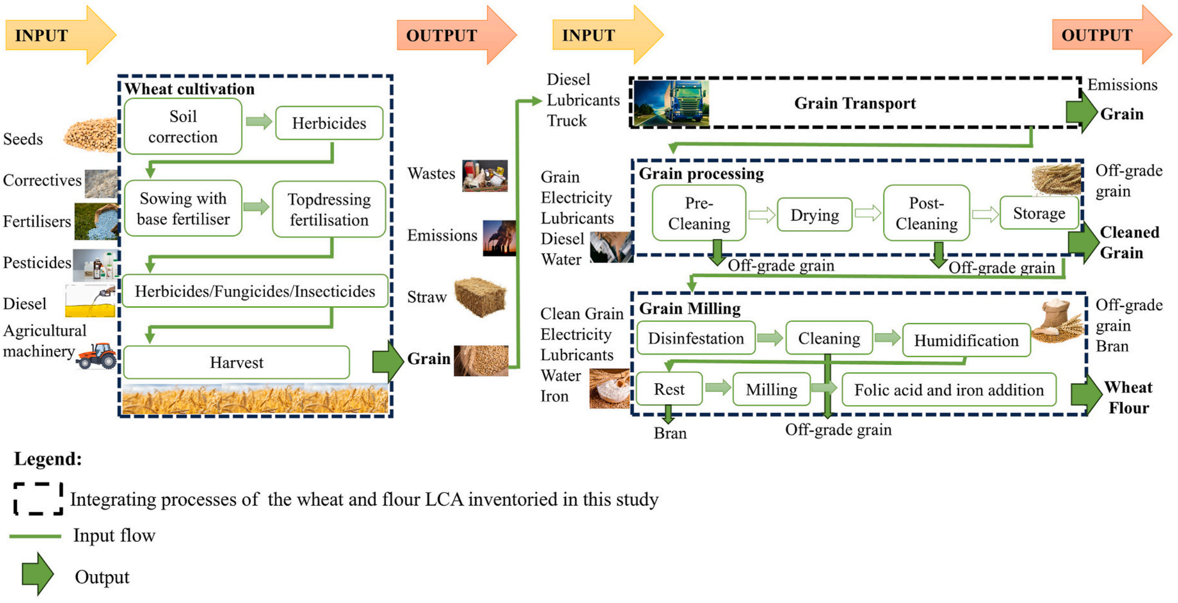

Fig. 2. Description of the systems analysed for the production of 1 kg of wheat grains and 1 kg of wheat flour.

harvest season, considering both loaded and empty truck fuel efficiency. Based on truck capacity, 32% of the harvested grains were transported by Mercedes-Benz 1313, and 68% transported by Volvo FH.

2.3.3. *Grain processing*

The 3324 m^2 industrial area at Moageira Irati, established in 2009, processes wheat through classification, pre-cleaning, drying and cleaning. Pre-cleaning removes broken grains, straw, and foreign matter, generating the first off-grade grain. Cleaning, conducted after drying, yields a second off-grade grain. Cleaned wheat is stored in silos and Phosphine is applied as needed.

2.3.4. *Grain milling*

The 5700 m^2 mill was established in 2022 and processes wheat through several stages. Grain is disinfected, cleaned, and then conditioned to a 4% moisture content. The milling process involves three stages: crushing, reduction, and compression. The milled flour is sieved to separate particles based on size. Finally, iron (4.2 mg kg^{-1}) and folic acid (150 mcg kg^{-1}) are added to the flour before storage or packaging.

2.4. Inventory data

Data on inputs and processes (Annex D, SM) for wheat and wheat flour production were directly collected through interviews with farmers, technical managers, and experts at Moageira Irati. The 61 farms were categorised into large and small (Annex B, SM), and data were collected over three consecutive years (2021–2023). The life cycle inventory (LCI) for wheat cultivation was developed using ICVcalc (Folegatti-Matsuura et al., 2022), while data for transport, grain processing, and milling were collected and added to SimaPro. Ecoinvent® v.3.9.1 was used to account for additional processes (Annex C, SM). To produce 1 kg of wheat flour, approximately 1.39 kg of raw wheat grain is required due to field losses and processing steps. After cleaning and drying, 1.30 kg of clean grain. By-products, such as bran and off-grade grains, are used as animal feeds.

2.5. Calculation of emissions

The BRcalc method, developed for Brazilian agricultural conditions (Folegatti-Matsuura et al., 2022), was used to calculate emissions. N_2O and CO_2 emissions were estimated using IPCC et al. (2019) equations, while NOx emissions followed Nemecek et al. (2016). P emissions to water and heavy metal emissions to soil were calculated using the World Food LCA Database (WFLDB) (Nemecek et al., 2015), adapted for Brazilian river basins. Pesticide emissions were determined using PestLCI (Dijkman et al., 2012). Detailed calculations and data are provided in the supplementary material (Annexes D and E). Land use change and soil carbon stock were not considered as the cultivated areas have been under no-till for over 30 years, indicating stable soil carbon stocks (Maciel et al., 2022; Tiecher et al., 2020). Additionally, the environmental impacts of farms and mill infrastructure were not included due to their long lifespan and diluted impact over time.

2.6. Allocation criteria

By-products such as bran and off-grade grains are generated along the supply chain of wheat flour production. Therefore, a mass allocation was performed to account for a fair division of environmental burdens (Annex F, SM). In grain processing, the majority of environmental burdens is allocated to clean grain, with only a small fraction assigned to off-grade grain. In the wheat milling process, wheat flour, bran and off-grade grain produced received 74.46%, 24.80% and 0.74%, respectively, of the environmental burden. This allocation method ensures a balanced distribution of environmental impacts across the primary and by-products of wheat flour production.

2.7. Life cycle impact assessment

The carbon footprint was calculated using the IPCC et al. (2019) GWP100 V1.03 method. The other environmental impacts were estimated using the AWARE V1.05 and ReCiPe 2016 Midpoint (H) V1.08/World (2010) H methods. The categories considered in this study were: Water Consumption Potential (WCP), Terrestrial Acidification Potential (TAP), Terrestrial Ecotoxicity (TET), Freshwater Eutrophication Potential (FEP), Marine Eutrophication Potential (MEP), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET), Human Toxicity Potential Cancer (HTPc) and Human Toxicity Potential non-cancer (HTPnc). All impacts were calculated using SimaPro 9.5.0.2 software and information from the Ecoinvent® database v3.5.

2.8. Sensitivity and uncertainty analysis

Using SimaPro data modelling, we analyse two scenarios to reduce environmental impacts in wheat cultivation. In Scenario 1, we replace urea with CAN fertiliser produced in Europe, which generates lower production impacts and emits less fossil CO_2 in the field (Galusnyak et al., 2023). Large and small farms that applied 155 and 148 kg ha^{-1} of urea were substituted with 265 and 253 kg ha^{-1} of CAN, respectively. In Scenario 2, we introduce a higher-yield wheat cultivar developed by Embrapa, with an average productivity of 5876 kg ha^{-1} based on nine years of studies on productive wheat genotypes (Castro et al., 2022). In the industrial phase of wheat flour production, we modelled the substitution of the energy matrix in Southern Brazil, where hydroelectric power contributes 57% of total generation, by the use of photovoltaic energy in the grain processing (Scenario 3) and milling (Scenario 4).

To compare processes A and B (Annex G, SM), a probabilistic uncertainty analysis was conducted using Monte Carlo with a 95% confidence interval (Goedkoop, 2008). Inventory data standard deviations were derived from the Pedigree Matrix, assuming a lognormal distribution for all variables. The comparison was performed over 1000 runs, counting the instances where $A-B < \text{zero}$ for each impact category. This count was then divided by the total runs (1000). If $A-B < \text{zero}$ occurred in 95% or more of runs for a given category, the impact of process A was considered significantly lower than B.

3. Results

3.1. Wheat flour production

Wheat cultivation was the primary source of environmental impacts in Brazilian wheat flour production, contributing between 67% and 98% across eight of the ten impact categories analysed, regardless of farm size (Table 1). Grain transportation to the mill had a negligible impact on the carbon footprint (GWP), contributing less than 1.5%, with other impact categories showing even lower contributions. The upstream production of diesel fuel was the main environmental driver for grain transportation.

The grain processing had the lowest environmental impacts, contributing less than 0.5% in all categories analysed (Table 1). The grain milling had the most significant impact on the FEP category (55.8%), while contributions to other categories ranged from 1.9% to 27.1%. The high FEP impact is primarily attributed to the use of phosphine for pest control during grain storage prior to milling. The WCP in the grain processing and grain milling was negative because water was used solely to clean equipment and it was returned to water bodies with a low residual load.

3.2. Wheat cultivation and sensitivity analysis: suggested scenarios

Given that wheat cultivation was the process with the most significant impact on flour production, a detailed analysis of the most influential cultivation factors is necessary. Three of the ten categories analysed showed a significant difference (Monte Carlo, 95% iterations) between large and small farms: FEP, TET, and FET. In the FEP category, small farms exhibited a higher impact due to applying P- and N-based fertilisers (Fig. 3D). In the TET and FET categories, significant impacts occurred on large farms. For TET, field emissions were the most impactful cultivation factor (36.2%), followed by the use of phosphate fertilisers (16.1%) (Fig. 3 F). In contrast, in the FET category, the use of phosphate fertilisers accounted for approximately 50% of the environmental impact.

Analysing the GWP category, there was no significant difference between large and small farms (0.47 and 0.58 kg CO_2eq kg wheat^{-1}) (Fig. 3A). The weighted average carbon footprint for Brazilian wheat grain production was 0.50 kg CO_2eq kg wheat^{-1}. Field emissions accounted for 59.4% of the cultivation factors that most affected the carbon footprint. Upstream processes related to the production of nitrogen and phosphate fertilisers contributed 20.9% and 7.5%, respectively, due to the energy required for their production (Fig. 3A).

Field emissions remained the primary cultivation factor impacting the other four categories analysed: TAP, MEP, TET, and MET (Fig. 3C–E, F, H). Different cultivation factors stood out in the categories: (1) WCP,

Table 1
Environmental impact categories and the contribution of each process to the production of 1 kg of Brazilian wheat flour.

Damage category	Unit	LF cultivation[a]	SF cultivation[a]	Grain Transport[a]	Grain Processing[a]	Grain Milling	LF Total	SF Total
GWP	kg CO_2e	6.59E-01	8.02E-01	1.16E-02	1.40E-03	3.16E-02	7.04E-01	8.47E-01
WCP	m^3	2.45E-01	2.82E-01	8.54E-05	−8.64E-04	−1.51E+00	−1.27E+00	−1.23E+00
TAP	kg SO_2 eq	1.08E-02	1.30E-02	6.73E-06	6.88E-06	1.83E-04	1.10E-02	1.32E-02
FEP	kg P eq	2.57E-04	1.33E-04	2.66E-08	6.09E-07	2.31E-04	4.89E-04	3.64E-04
MEP	kg N eq	3.76E-03	4.46E-03	3.86E-07	2.81E-07	2.69E-04	4.03E-03	4.73E-03
TET	kg 1,4-DCB	2.45E+00	2.23E+00	4.53E-03	1.21E-03	1.92E-01	2.65E+00	2.43E+00
FET	kg 1,4-DCB	1.66E-02	1.07E-02	7.02E-06	1.52E-05	3.57E-03	2.02E-02	1.43E-02
MET	kg 1,4-DCB	3.93E-02	3.64E-02	2.36E-05	2.16E-05	4.80E-03	4.41E-02	4.12E-02
HTPc	kg 1,4-DCB	1.04E-02	1.03E-02	5.04E-06	6.86E-05	8.10E-03	1.86E-02	1.84E-02
HTPnc	kg 1,4-DCB	6.78E-01	3.54E-01	2.89E-04	7.59E-04	1.25E-01	8.04E-01	4.80E-01

LF = Large farm; SF = Small farm; GWP = Global warming potential; WCP = Water consumption potential; TAP = Terrestrial acidification potential; FEP = Freshwater eutrophication potential; MEP = Marine eutrophication potential; TET = Terrestrial ecotoxicity; FET = Freshwater ecotoxicity; MET = Marine ecotoxicity; HTPc = Human toxicity potential: cancer; HNT = Human toxicity potential: non-cancer.

[a] To produce 1 kg of wheat flour, 1.39 kg of wheat grains are used in cultivation and grain transport; and 1.3 wheat grains are used in grain milling.

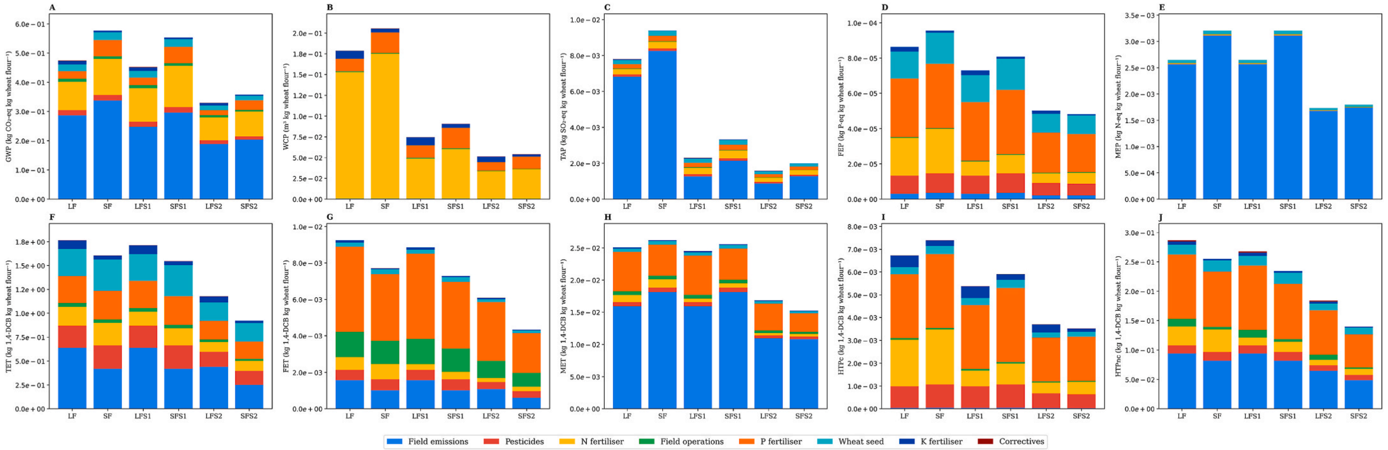

Fig. 3. Environmental impact categories and the contribution of cultivation factors for the production of 1 kg of Brazilian wheat from the current crop and the two proposed scenarios. LF = Large farm; SF = Small farm; LFS1 = Large farm scenario 1; LFS2 = Large farm scenario 2; SFS1 = Small farm scenario 1; SFS2 = Small farm scenario 2; A) GWP = Global warning potential; B) WCP = Water consumption potential; C) TAP = Terrestrial acidification potential; D) FEP = Freshwater eutrophication potential; E) MEP = Marine eutrophication potential; F) TET = Terrestrial ecotoxicity; G) FET = Freshwater ecotoxicity; H) MET = Marine ecotoxicity; I) HTPc = Human toxicity potential: cancer; J) HTPnc = Human toxicity potential: non-cancer.

which was impacted by upstream processes of nitrogen fertiliser production (Fig. 3B); (2) FEP, FET, HTPc, and HNTnc, where phosphate fertilisers were the most impactful cultivation factor (Fig. 3D–G, I, J). Specific impacts of pesticides occurred in the FEP (12.4%), TET (14.2%), and HTPc (14%) categories, considering the average of large and small farms. Wheat seed production impacted FEP (19.1%) and TET (18.1%) (Fig. 3D and F). Field operations, where fuels are the primary contributors, stood out only in the FET category, contributing 14.9% and 16.5% on large and small farms, respectively (Fig. 3G).

An analysis of environmental impact categories indicates that replacing urea with CAN (scenario 1) significantly decreased TAP and FEP in both farm sizes. At the same time, FET and MET reductions were more pronounced in larger farms (Fig. 3, Annex G SM). Scenario 2, including higher-yielding wheat genotypes, led to substantial reductions in six of the ten analysed categories for both farm types: TAP, FEP, MEP, TET, FET, and MET. Notably, GWP decreased significantly only in small farms. WCP, HTPc, and HTPnc categories showed no significant differences with the scenarios (Fig. 3, Annex G, SM).

3.3. *Environmental impacts and suggested scenarios in wheat flour production processes*

The most significant environmental impact in the grain processing and milling was attributed to electricity consumption. Photovoltaic energy significantly reduced the environmental impact of grain processing (scenario 3) across five categories: GWP, TAP, FEP, MEP, and TET (Annex G, SM). However, in the grain milling (scenario 3), only the GWP and TAP were reduced (Table 2).

The combined strategy of substituting urea with CAN (scenario 1), increasing productivity (scenario 2), and adopting a photovoltaic energy matrix (scenarios 3 and 4) resulted in the most substantial reduction in the TAP category (78%), followed by HTPnc (41%) and HTPnc (40%) (Table 3). TET, FET, and MET, as well as GWP and MEP, exhibited reductions ranging from 34% to 39%. FEP decreased by an average of 24%, whereas WCP remained unaffected (Table 3).

4. Discussion

4.1. *Key drivers of environmental impacts in wheat cultivation and flour production*

Wheat cultivation was the main contributor to environmental impacts in wheat flour production, with field emissions driven by nitrogen (N) and phosphorus (P) fertilisers as the most significant factor. These fertilisers release greenhouse gases (GHGs) (Nadarajan and Sukumaran, 2021). Phosphatic fertilisers contributed significantly to FEP, TET, and FET (Fig. 3); however, due to low P levels in Brazilian soils (Pavinato et al., 2020) and reliance on imported phosphorus, alternatives remain a long-term prospect (Raniro et al., 2023). Nitrogenous fertilisers affected GWP, WCP, FET, and HTPc.

Table 2
Environmental impact categories for grain processing and grain milling using the local energy matrix versus substitution with photovoltaic energy (scenarios 3 and 4) for the production of 1 kg of Brazilian wheat flour.

Damage category	Unit	GP	GPS3	GM	GMS4
GWP100	kg CO_2-eq	1.40E-03	2.48E-04	3.16E-02	2.04E-02
Water use	m^3	−8.64E-04	−1.25E-03	−1.51E+00	−1.52E+00
Terrestrial acidification	kg SO_2 eq	6.88E-06	3.23E-07	1.83E-04	1.19E-04
Freshwater eutrophication	kg P eq	6.09E-07	2.02E-07	2.31E-04	2.27E-04
Marine eutrophication	kg N eq	2.81E-07	2.28E-07	2.69E-04	2.69E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.21E-03	4.18E-04	1.92E-01	1.84E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.52E-05	3.42E-06	3.57E-03	3.46E-03
Marine ecotoxicity	kg 1,4-DCB	2.16E-05	4.85E-06	4.80E-03	4.63E-03
Human carcinogenic toxicity	kg 1,4-DCB	6.86E-05	8.24E-06	8.10E-03	7.50E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	7.59E-04	1.25E-04	1.25E-01	1.19E-01

GP = Grain processing; GPS3 = Grain processing scenario 3; GM = Grain Milling; GMS4 = Grain Milling scenario 4.

Replacing urea with CAN (Scenario 1) showed minimal GWP reduction, as N_2O emissions from nitrogen fertilisers remained the main contributor to field emissions (Fig. 3A). However, CAN substitution lowered fossil CO_2 emissions (Fig. 3A). Urea increases CO_2 emissions due to its synthesis from ammonia and CO_2, raising GHG emissions by about 40% due to high carbon content (Galusnyak et al., 2023). Urea also volatilises faster, reducing nitrogen uptake efficiency (Govindasamy et al., 2023). In contrast, CAN, with no carbon atoms, produces minimal CO_2 emissions in fields (Galusnyak et al., 2023). Beyond urea substitution, alternatives like cover cropping with nitrogen-fixing species should be encouraged to reduce synthetic nitrogen fertiliser use (Bansal et al., 2022).

The strategy of selecting improved cultivars (Scenario 2) emerged as the most effective in reducing GWP (Fig. 3A, LFS2, SFS2) and six other impact categories on LF and SF (Fig. 3, Annex G). This approach significantly reduced specific impacts from pesticides, seed production, and field operations, aligning with Climate-Smart Agriculture (CSA) strategies (Maraseni et al., 2021). Field research using CSA data shows a 41.4% reduction in carbon footprint with higher-yield maise varieties (Feng et al., 2023b).

The remaining processes of wheat flour production had low environmental impacts in the analysed categories, except for FEP, which was higher in the grain milling process (section 3.1). In grain wheat processing and wheat milling, replacing the current energy matrix with photovoltaic energy reduced environmental impacts, primarily GWP and TAP. This result confirms the importance of increased investment in clean energy production to make industrial processes more environmentally sustainable (Rafiee et al., 2024).

Table 3
Contribution of each process to the production of 1 kg of Brazilian wheat flour to reduce environmental impacts through the scenarios.

Damage category for 1 kg of wheat	LFS1	SFS1	LFS2	SFS2	GT	GPS3	GM S4	LFS Total	SFS Total	LF x LFS (%)[a]	SF X SFS (%)[a]	Mean (%)[a]
GWP100 (kg CO_2-eq)	6.29E-01	7.69E-01	4.58E-01	4.97E-01	1.16E-02	2.48E-04	2.04E-02	4.90E-01	5.29E-01	30.37	37.55	33.96
Water use (m^3)	1.00E-01	1.23E-01	6.91E-02	7.30E-02	8.54E-05	−1.25E-03	−1.52E+00	−1.45E+00	−1.44E+00	14.23	17.34	15.79
Terrestrial acidification (kg SO_2 eq)	3.19E-03	4.62E-03	2.19E-03	2.75E-03	6.73E-06	3.23E-07	1.19E-04	2.32E-03	2.88E-03	78.99	78.26	78.63
Freshwater eutrophication (kg P eq)	1.01E-04	1.12E-04	6.97E-05	6.69E-05	2.66E-08	2.02E-07	2.27E-04	2.97E-04	2.94E-04	39.29	19.31	29.30
Marine eutrophication (kg N eq)	3.68E-03	4.46E-03	2.41E-03	2.50E-03	3.86E-07	2.28E-07	2.69E-04	2.68E-03	2.76E-03	33.55	41.51	37.53
Terrestrial ecotoxicity (kg 1.4-DCB)	2.38E+00	2.15E+00	1.64E+00	1.28E+00	4.53E-03	4.18E-04	1.84E-01	1.83E+00	1.47E+00	31.14	39.46	35.30
Freshwater ecotoxicity (kg 1.4-DCB)	1.23E-02	1.01E-02	8.46E-03	6.02E-03	7.02E-06	3.42E-06	3.46E-03	1.19E-02	9.49E-03	40.81	33.63	37.22
Marine ecotoxicity (kg 1.4-DCB)	3.41E-02	3.55E-02	2.34E-02	2.12E-02	2.36E-05	4.85E-06	4.63E-03	2.81E-02	2.58E-02	36.38	37.37	36.88
Human carcinogenic toxicity (kg 1.4-DCB)	7.48E-03	8.21E-03	5.14E-03	4.89E-03	5.04E-06	8.24E-06	7.50E-03	1.27E-02	1.24E-02	32.02	32.76	32.39
Human non-carcinogenic toxicity (kg 1.4-DCB)	3.72E-01	3.25E-01	2.56E-01	1.94E-01	2.89E-04	1.25E-04	1.19E-01	3.75E-01	3.13E-01	53.39	34.86	44.12

LF = Large farm; SF = Small farm; LFS1 = Large farm scenario 1; LFS2 = Large farm scenario 2; SFS1 = Small farm scenario 1; SFS2 = Small farm scenario 2; GT = Grain transport; GP = Grain processing; GPS3 = Grain processing scenario 3; GM = Grain Milling; GMS4 = Grain Milling scenario 4.

[a] % of reduction.

4.2. Environmental impacts of Brazilian wheat flour production compared to other parts of the world

Brazilian dryland wheat production (0.50 kg CO_2eq kg wheat-1), positions itself as a medium emitter compared to other wheat-producing countries. While below the global average of 0.60 kg CO_2eq kg^{-1} (Feng et al., 2023a), it exceeds countries like Germany (Riedesel et al., 2022) and Australia (Simmons et al., 2019), with 0.35 and 0.37 kg CO_2eq kg^{-1}, respectively (Fig. 4). This variation is influenced by factors such as climate, soil type, agricultural practices, and input use, particularly nitrogen fertilisers. In Brazilian wheat cultivation, farmers that use CAN combined with the adoption of more productive cultivars (Castro et al., 2022) have a strategy to reduce the carbon footprint of wheat. These measures can optimise fertiliser use, decrease greenhouse gas emissions, and increase production efficiency.

Considering other categories, Brazilian wheat production shows favourable environmental impacts compared to those reported in other countries (Table 4). Rainfed wheat production reduces WCP from water bodies to nearly zero during the wheat growth phase. The WCP, in the cultivation process, was primarily impacted by WCP in the synthesis of NPK fertilisers. Rising food and fertiliser demand from population growth is prompting fertiliser industries to adopt water treatment and reuse solutions to ease pressure on water bodies (Fiamelda and Suprihatin, 2020).

TAP was the category with the highest impact compared to other countries (Table 4). However, significant reductions were achieved by replacing urea with CAN in Scenario 1 (67.6%) and by increasing productivity in Scenario 2 (79.3%) (Table 3). When urea is not absorbed by plants or leached as nitrate, it can lead to soil acidification due to rapid hydrolysis and nitrification reactions of NH_4^+, releasing two H^+ ions (Dal Molin et al., 2020). Conversely, CAN fertilisers help minimise soil acidity due to their calcium content (Akanova et al., 2021).

Studies reporting data on the environmental impacts of wheat flour production are scarce worldwide (Fig. 5). Most studies have focused on the LCA of wheat cultivation, and some have progressed to determine the environmental impacts of bread production (Rafiee et al., 2024). Few studies have reported on the processes of wheat flour production (Kulak et al., 2015; Câmara Salim et al., 2020), and another presented data on total wheat flour production (Pourmehdi and Kheiralipour, 2020) (Fig. 5). In these studies, GWP ranged from 0.50 to 1.66 kg CO_2eq kg wheat flour^{-1}. This variation is expected as climatic conditions and management practices differ from region to region (Câmara Salim et al., 2020).

Brazilian wheat flour holds a favourable position, with current C footprints for large and small farms (0.67 and 0.80 kg CO_2eq per kg) below those of Spain and Italy (0.89 and 0.95 kg CO_2eq per kg, respectively) (Câmara-Salim et al., 2020; Kulak et al., 2015). Scenario 2 C footprints (0.48 and 0.52 kg CO_2eq per kg for LF and SF, respectively) are also close to the lowest levels reported in France and Portugal, both at 0.50 kg CO_2eq per kg (Kulak et al., 2015).

Brazilian wheat flour production showed higher impacts than other countries in TAP and TET categories (Fig. 5), primarily due to cultivation-related field emissions, fertiliser, and pesticide use. In other categories, Brazil exhibits lower environmental impacts than other wheat flour producers. Our results suggest that with more efficient wheat cultivars, Brazilian flour production could rank among the most sustainable globally (Fig. 5). The current environmental impacts and how strategies can reduce them, as demonstrated in this study, highlight ways to mitigate GHG emissions and other pollutants from one of the world's most consumed foods.

4.3. Reducing environmental impact factors: general perspectives, limitations, and recommendations

Field emissions and nitrogen and phosphate fertiliser production were the main contributors to environmental impact in Brazilian wheat cultivation and flour production. Field emissions reflect the management practices and inputs used. Replacing urea with CAN from Europe, as in Scenario 1, could reduce the C footprint by 4%, a modest improvement. However, applying the average reduction of 0.023 kg CO_2eq per kg of wheat to Brazil's 2023 production of 8096.8 thousand tonnes (CONAB- Companhia Nacional de Abastecimento, 2024) would result in 184.6 fewer tonnes of CO_2eq emissions. With a 34% reduction in Scenario 2, 1476.3 CO_2eq tonnes could be avoided.

Beyond urea substitution and productivity gains proposed in this study, other technologies should be considered to reduce environmental

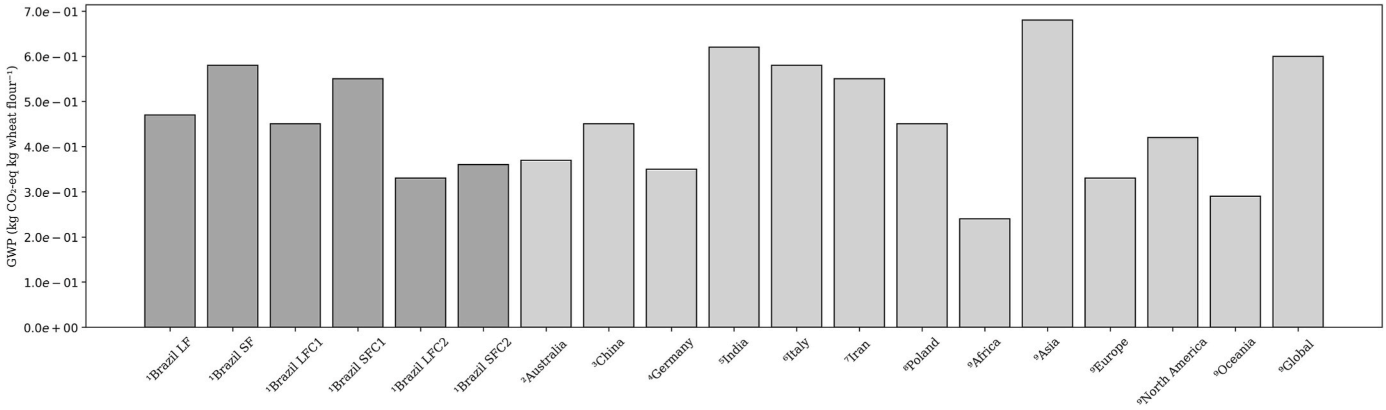

Fig. 4. Comparison of the carbon footprint for the production of 1 kg of Brazilian wheat in the current scenario and in the proposed scenarios with other wheat producing countries. LF = Large farm; SF = Small farm; LFC1 = Large farm scenario 1; LFC2 = Large farm scenario 2; SFC1 = Small farm scenario 1; SFC2 = Small farm scenario 2.

[1] Our study
[2] Simmons et al. (2019)
[3] Shao et al. (2024)
[4] Riedesel et al. (2022)
[5] Nayak et al. (2023)
[6] Verdi et al. (2022)
[7] Tahmasebi et al. (2018)
[8] Pishgar-Komleh et al. (2020)
[9] Feng et al. (2023a)

Table 4

Comparison of environmental impact categories for the production of 1 kg of Brazilian wheat current and in the proposed scenarios with other wheat producing countries.

Damage category	WCP	TAP	FEP	MEP	TET	FET	MET	HTPc	HTPnc
Unit	m3	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB
Brazil LF[a]	1.76E-01	7.79E-03	8.63E-05	2.65E-03	1.77E+00	9.24E-03	2.51E-02	6.73E-03	2.87E-01
Brazil SF[a]	2.03E-01	9.39E-03	9.56E-05	3.21E-03	1.60E+00	7.70E-03	2.62E-02	7.39E-03	2.55E-01
Brazil LFC1[a]	7.23E-02	2.29E-03	7.29E-05	2.65E-03	1.71E+00	8.86E-03	2.45E-02	5.38E-03	2.68E-01
Brazil SFC1[a]	8.82E-02	3.33E-03	8.08E-05	3.21E-03	1.55E+00	7.28E-03	2.56E-02	5.90E-03	2.34E-01
Brazil LFC2[a]	4.97E-02	1.58E-03	5.01E-05	1.73E-03	1.18E+00	6.09E-03	1.68E-02	3.70E-03	1.84E-01
Brazil SFC2[a]	5.25E-02	1.98E-03	4.81E-05	1.80E-03	9.21E-01	4.33E-03	1.52E-02	3.52E-03	1.39E-01
China[b]	7.71E-01	4.83E-03	2.51E-04	2.31E-04	2.88E+00	2.53E-02	3.52E-02	3.52E-02	1.29E+00
Europe[c]	–	5.70E-03	8.50E-05	6.29E-03	–	–	–	–	–
India[d]	–	3.27E-03	1.80E-04	4.40E-04	–	3.62E-02	1.86E+02	2.42E+00	1.71E+02
Iran[e]	–	1.19E-02	–	–	6.90E-04	5.34E-02	2.76E+02	1.00E-01	–
Italy[f]	6.06E-04	3.90E-03	–	–	5.80E-04	5.00E-02	1.70E+02	1.10E-01	–
Slovakia[g]	5.92E-04	1.76E-03	7.07E-05	5.07E-04	4.26E-01	8.79E-03	5.30E-03	–	–
USA[h]	–	–	5.00E-04	–	–	7.00E-05	–	–	–

LF = Large farm; SF = Small farm; LFC1 = Large farm scenario 1; LFC2 = Large farm scenario 2; SFC1 = Small farm scenario 1; SFC2 = Small farm scenario 2; WCP = Water consumption potential; TAP = Terrestrial acidification potential; FEP = Freshwater eutrophication potential; MEP = Marine eutrophication potential; TET = Terrestrial ecotoxicity; FET = Freshwater ecotoxicity; MET = Marine ecotoxicity; HTPc = Human toxicity potential: cancer; HTPnc = Human toxicity potential: non-cancer.

[a] Our study.

[b] Jiang et al. (2021).

[c] Achten and Van Acker (2016).

[d] Khangar and Thangavel (2024).

[e] Taki et al. (2018).

[f] Verdi et al. (2022).

[g] Mukosha et al. (2023).

[h] Shrestha et al. (2020).

impacts and reliance on synthetic fertilisers. Biofertilisers, biopesticides, slow-release fertilisers, and nanofertilisers (Nadarajan and Sukumaran, 2021) offer potential for impact reduction in Brazilian rainfed wheat production. Research is also exploring green urea and ammonium nitrate production using renewable rather than fossil energy sources, supporting net-zero emissions targets for 2050 (Galusnyak et al., 2023).

This study has limitations to consider when interpreting results. Firstly, our study addressed LCA of rainfed wheat cultivation, excluding irrigated wheat cultivation, which is expanding into new regions and may significantly affect environmental impacts. Additionally, the study simulated scenarios for input substitution, productivity increases, and energy replacement; while literature supports these, large-scale implementation may face economic and technological challenges. Finally, impact analyses were limited to ten standard LCA categories, but factors like biodiversity and soil health are also key to understanding wheat production sustainability. Future studies incorporating these could offer a more complete view of environmental impacts and mitigation opportunities for wheat in subtropical and tropical regions.

Our findings can guide producers, researchers, and policymakers in identifying effective solutions to reduce N_2O emissions, the main contributor to CO_2eq emissions in wheat cultivation, through the efficient use of fertilisers. Using better-adapted and more productive cultivars that require the same amount of inputs is an effective way to optimise input use and reduce the environmental impacts of wheat cultivation. Regarding grain processing and milling, using photovoltaic energy proved to be a strategic option for reducing production impacts in the industrial phase of flour production.

5. Conclusion

The life cycle assessment of wheat flour revealed that wheat cultivation is the primary emitter of greenhouse gases and particulate pollutants. Farm size, fertilisers and wheat cultivars directly affected environmental impacts. Large farms exhibited lower environmental impacts compared to small farms due to higher productivity, indicating that field inputs, field operation and productivity need to be improved among small farmers. Sensitivity analysis demonstrated that increasing productivity without increasing inputs reduces environmental impacts.

In alignment with sustainable intensification goals, research should prioritise the development of high-yield wheat cultivars adapted to each cultivation region. Such efforts could reduce environmental impact per unit of production while minimising pressure on natural resources to meet the growing global demand for food. The substitution of urea with CAN had a low impact on the GWP. CAN reduce the impact of other impact categories such as WCP, TAP, and FEP, indicating that farmers should consider using more sustainable fertilisers. Further research into strategies for the efficient use of nitrogen fertiliser and alternative solutions like legume-based cover crop mixtures, biofertilisers, green ammonia and slow-release formulations is essential for achieving sustainability. In the industrial phase of wheat flour production, including the wheat processing and wheat milling processes, photovoltaic energy reduces environmental impacts, reinforcing the role of renewable energy sources in the industrial process to align with cleaner production principles. By quantifying these impacts in feasible scenarios, this study fills a critical gap in the LCA literature with new insights into the environmental impacts of wheat cultivation and flour production in non-temperate regions.

A comparison with other LCA studies indicates that Brazilian wheat flour production is among the most sustainable globally. However, the wheat cultivation process needs to focus on minimising its environmental impacts, mainly by reducing field emissions. Addressing more studies about the mitigation of environmental impacts is an important step towards making wheat and wheat flour production one of the most environmentally sustainable in the world, especially in terms of direct N_2O volatilisation. Other potential research directions could include integrating the social life cycle assessment (S-LCA) and life cycle costing (LCC) into the environmental LCA. This approach leads to analysing the social and economic implications associated with innovative technologies to gain insights into their financial viability, scalability, and social impacts on farming communities and industrial stakeholders. Combining these methods can address the sustainability aspects of wheat cultivation and wheat flour production more comprehensively. We believe that the strategies proposed, such as the substitution of urea, increasing wheat yield through more adapted cultivars, and the use of

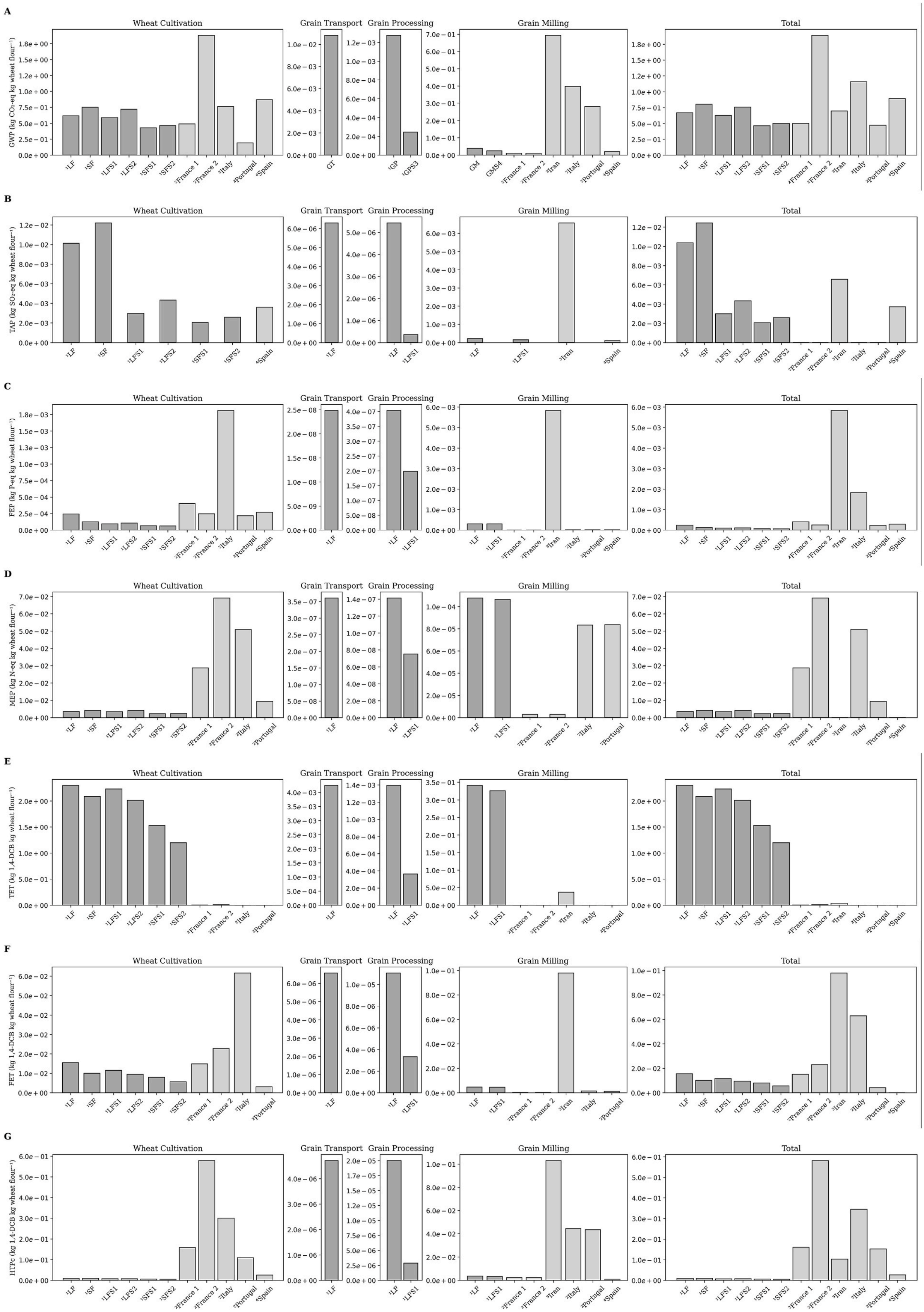

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Fig. 5. Comparison of the environmental impact categories for the production of 1 kg of Brazilian wheat flour current and in the proposed scenarios with other wheat flour producing countries. LF = Large farm; SF = Small farm; LFC1 = Large farm scenario 1; LFC2 = Large farm scenario 2; SFC1 = Small farm scenario 1; SFC2 = Small farm scenario 2.
[1]Our study
[2]Kulak et al. (2015)
[3]Câmara-Salim et al. (2020)
[4]Pourmehdi and Kheiralipour (2020).

photovoltaic energy, can assist farmers, millers, and public policymakers in making Brazilian wheat flour production more sustainable and competitive in the global scenario as well as provide insights into wheat cultivation for subtropical and tropical environments.

CRediT authorship contribution statement

Vanderlise Giongo: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adão da Silva Acosta:** Investigation, Formal analysis, Data curation. **Álvaro Augusto Dossa:** Investigation, Formal analysis, Data curation. **Anderson Santi:** Writing – review & editing, Investigation. **André Júlio do Amaral:** Writing – review & editing, Investigation. **Eduardo Caierão:** Writing – review & editing, Investigation. **José Eloir Denardin:** Writing – review & editing, Investigation. **Osvaldo Vasconcellos Vieira:** Writing – review & editing, Funding acquisition. **Maria Cléa Brito de Figueirêdo:** Methodology, Conceptualization. **Marília Ieda da Silveira Folegatti:** Methodology, Conceptualization. **José Paulo Pereira das Dores Savioli:** Validation, Formal analysis, Data curation. **Tatiane Battistelli Martins:** Investigation, Data curation. **Bruno Ricardo Silva:** Investigation, Data curation. **Bruno Stephano Pires:** Investigation, Data curation. **Mônica da Silva Santana:** Writing – original draft, Validation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vanderlise Giongo reports financial support was provided by FAPEG - Edmundo Gastal Agricultural Research and Development Support Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.144650.

Data availability

Data will be made available on request.

References

Achten, W.M., Van Acker, K., 2016. EU-average impacts of wheat production: a meta-analysis of life cycle assessments. J. Ind. Ecol. 20 (1), 132–144. https://doi.org/10.1111/jiec.12278.

Akanova, N.I., Vizirskaya, M.M., Zhdanov, V.Y., 2021. Prospects for the use of calcium ammonium nitrate on acidic soils of the Non-Black Earth Area. In: E3S Web Conf., vol. 285. EDP Sciences, p. 6010. https://doi.org/10.1051/e3sconf/202128506010.

Bansal, S., Yin, X., Schneider, L., Sykes, V., Jagadamma, S., Lee, J., 2022. Carbon footprint and net carbon gain of major long-term cropping systems under no-tillage. J. Environ. Manag. 307, 114505. https://doi.org/10.1016/j.jenvman.2022.114505.

Câmara-Salim, I., Almeida-Garcia, F., Gonzalez-Garcia, S., Romero-Rodriguez, A., Ruiz-Nogueiras, B., Pereira-Lorenzo, S., Feijoo, G., Moreira, M.T., 2020. Life cycle assessment of autochthonous varieties of wheat and artisanal bread production in Galicia, Spain. Sci. Total Environ. 713, 136720. https://doi.org/10.1016/j.scitotenv.2020.136720.

Castro, R.L., Caierão, E., Pires, J.L.F., Toigo, M.C., Aires, R.F., Rosa, A.C., Tomazzi, D.J., Santos, F.M., Corassa, G.M., Facco, G., Hörbe, T.A.N., 2022. Ensaio estadual de cultivares de trigo: safra 2021. Reunião Da Comissão Brasileira de Pesquisa de Trigo e Triticale 15, 220–224.

CONAB- Companhia Nacional de Abastecimento, 2024. Trigo – Brasil Série histórica de área plantada, safras 1976 a 2023, em mil hectares. https://www.conab.gov.br/info-agro/safras/serie-historica-das-safras/itemlist/category/913-trigo. (Accessed 4 June 2024).

Dal Molin, S.J., Ernani, P.R., Gerber, J.M., 2020. Soil acidification and nitrogen release following application of nitrogen fertilizers. Commun. Soil Sci Plant Anal 51 (20), 2551–2558. https://doi.org/10.1080/00103624.2020.1845347.

Dijkman, T.J., Birkved, M., Hauschild, M.Z., 2012. PestLCI 2.0: a second generation model for estimating emissions of pesticides from arable land in LCA. Int. J. Life Cycle Assess. 17, 973–986. https://doi.org/10.1007/s11367-012-0439-2.

Feng, S., Lakshmanan, P., Zhang, Y., Zhang, T., Liang, T., Zhang, W., Chen, X., Wang, X., 2023a. A comprehensive continental-scale analysis of carbon footprint of food production: comparing continents around the world. J. Clean. Prod. 426, 138939. https://doi.org/10.1016/j.jclepro.2023.138939.

Feng, X., Sun, T., Guo, J., Cai, H., Qian, C., Hao, Y., Yu, Y., Deng, A., Song, Z., Zhang, W., 2023b. Climate-smart agriculture practice promotes sustainable maize production in northeastern China: higher grain yield while less carbon footprint. Field Crops Res. 302, 109108. https://doi.org/10.1016/j.fcr.2023.109108.

Fiamelda, L., Suprihatin, Purwoko, 2020. Analysis of water and electricity consumption of urea fertilizer industry: case study PT. X. IOP Conf. Ser. Earth Environ. Sci. 472, 012034. https://doi.org/10.1088/1755-1315/472/1/012034.

Folegatti-Matsuura, M.D.S., Cardoso, F., Pighinelli, A., Maciel, V., Ramos, N., Garofalo, D., Mendes, N.C., Moore, C.C.S., Novaes, R.M.L., Morandi, M., 2022. ICVCalc: ferramenta para construção de inventários agrícolas para estudos de avaliação de ciclo de vida. Embrapa, Circular Técnica 32.

Galusnyak, S.C., Petrescu, L., Sandu, V.C., Cormos, C.C., 2023. Environmental impact assessment of green ammonia coupled with urea and ammonium nitrate production. J. Environ. Manag. 343, 118215. https://doi.org/10.1016/j.jenvman.2023.118215.

Goedkoop, M., 2008. SimaPro 7 Manual - Introduction into LCA 88.

Govindasamy, P., Muthusamy, S.K., Bagavathiannan, M., Mowrer, J., Jagannadham, P.T.K., Maity, A., Halli, H.M., Sujayananad, G.K., Vadivel, R., et al., 2023. Nitrogen use efficiency - a key to enhance crop productivity under a changing climate. Front. Plant Sci. 14, 1121073. https://doi.org/10.3389/fpls.2023.1121073.

IBGE - Instituto Brasileiro de Geografia e Estatística, 2023. Pam - produção agrícola municipal. https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9117-producao-agricola-municipal-culturas-temporarias-e-permanentes.html. (Accessed 8 July 2024).

Ibrahim, A.A., Abd-Ellatif, S., Abdel Razik, E.S.S., Salem, K.F.M., 2024. Biodiversity of cereal crops and utilization in food and nutritional security. In: Al-Khayri, J.M., Jain, S.M., Penna, S. (Eds.), Sustainable Utilization and Conservation of Plant Genetic Diversity. Sustainable Development and Biodiversity, vol. 35. Springer, Singapore. https://doi.org/10.1007/978-981-99-5245-8_2.

IPCC, 2019. In: Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S. (Eds.), 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Published: IPCC, Switzerland.

ISO - International Organization for Standardization, 2006a. ISO 14040:2006-Environmental Management, Life Cycle Assessment, Principles and Framework. ISO, Geneva.

ISO - International Organization for Standardization, 2006b. ISO 14044:2006-Environmental Management - Life Cycle Assessment - Requirements and Guidelines. ISO, Geneva.

ISO - International Organization for Standardization, 2014. ISO 14046: Environmental Management–Water Footprint–Principles, Requirements and Guidelines. ISO, Geneva.

ISO - International Organization for Standardization, 2018. ISO 14067: Greenhouse Gases–Carbon Footprint of Products–Requirements and Guidelines for Quantification. ISO, Geneva.

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.

Khangar, N.S., Thangavel, M., 2024. Assessment of environmental impacts: a life cycle analysis of wheat and rice production in Madhya Pradesh. Agron. Res. 22 (S2), 636–658. https://doi.org/10.15159/AR.24.011.

Kulak, M., Nemecek, T., Frossard, E., Chable, V., Gaillard, G., 2015. Life cycle assessment of bread from several alternative food networks in Europe. J. Clean. Prod. 90, 104–113. https://doi.org/10.1016/j.jclepro.2014.10.060.

Maciel, V.G., Novaes, R.M.L., Brandão, M., Cavalett, O., Pazianotto, R.A.A., Garofalo, D. T., Folegatti-Matsuura, M.I., 2022. Towards a non-ambiguous view of the amortization period for quantifying direct land-use change in LCA. Int. J. Life Cycle Assess. 27 (12), 1299–1315. https://doi.org/10.1007/s11367-022-02103-3.

Maraseni, T., An-Vo, D.A., Mushtaq, S., Reardon-Smith, K., 2021. Carbon smart agriculture: an integrated regional approach offers significant potential to increase profit and resource use efficiency, and reduce emissions. J. Clean. Prod. 282, 124555. https://doi.org/10.1016/j.jclepro.2020.124555.

Milani, P., Haddad, L., Steiner, R., Mkambula, P., Ehsani, M., Kamau, D., Ndung'u, D., Pee, S., 2024. Fortified whole grains and whole blends: a timely food systems shift. Global Food Secur. 42, 100784. https://doi.org/10.1016/j.gfs.2024.100784.

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 (11), 2068. https://doi.org/10.3390/agriculture13112068.

Nadarajan, S., Sukumaran, S., 2021. Chemistry and toxicology behind chemical fertilizers. In: Controlled Release Fertilizers for Sustainable Agriculture. Academic Press, pp. 195–229. https://doi.org/10.1016/B978-0-12-819555-0.00012-1.

Nayak, A.K., Tripathi, R., Debnath, M., Swain, C.K., Biswaranjan, D.H.A.L., Vijaykumar, S., Nayak, A.D., Mohanty, S., Shahid, M., Kumar, A., Rajak, M., 2023. Carbon and water footprints of major crop production in India. Pedosphere 33 (3), 448–462. https://doi.org/10.1016/j.pedsph.2022.06.045.

Nemecek, T., Bengoa, X., Lansche, J., Mouron, P., Riedener, E., Rossi, V., Humbert, S., 2015. Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. World Food LCA Database (WFLDB). Quantis and Agroscope, Lausanne and Zurich, Switzerland. Version 3.0, July 2015.

Nemecek, T., Schnetzer, J., Reinhard, J., 2016. Updated and harmonized greenhouse gas emissions for crop inventories. Int. J. Life Cycle Assess. 21 (9), 1361–1378.

Nóia Júnior, R.D.S., Nardino, M., Elli, E.F., Pequeno, D., Fraisse, C., Asseng, S., 2024. Achieving wheat self-sufficiency in Brazil. Environ. Res. Lett. 19 (3), 031003. https://doi.org/10.1088/1748-9326/ad26b8.

Pavinato, P.S., Cherubin, M.R., Soltangheisi, A., Rocha, G.C., Chadwick, D.R., Jones, D. L., 2020. Revealing soil legacy phosphorus to promote sustainable agriculture in Brazil. Sci. Rep. 10, 15615. https://doi.org/10.1038/s41598-020-72302-1.

Pishgar-Komleh, S.H., Zylowski, T., Rozakis, S., Kozyra, J., 2020. Efficiency under different methods for incorporating undesirable outputs in an LCA+ DEA framework: a case study of winter wheat production in Poland. J. Environ. Manag. 260, 110138. https://doi.org/10.1016/j.jenvman.2020.110138.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360 (6392), 987–992. https://doi.org/10.1126/science.aaq0216.

Pourmehdi, K., Kheiralipour, K., 2020. Assessing the effects of wheat flour production on the environment. Adv. Environ. Technol. 6 (2), 111–117. https://doi.org/10.22104/aet.2021.4704.1280.

Rafiee, M., Abbaspour-Fard, M.H., Heidari, A., 2024. Analyzing sustainability in bread production: a life cycle assessment approach to energy, exergy and environmental footprint. Environ. Sci. Pollut. Res. 31, 46949–46964. https://doi.org/10.1007/s11356-024-34121-z.

Raniro, H.R., Papera, J., José, L.U., Valença, R.M., Pavinato, P.S., Hermann, L., Santner, J., 2023. New investments in phosphorus research and training are paramount for Brazilian long-term environmental and food security. Environ. Syst. Decis. 43 (3), 504–508. https://doi.org/10.1007/s10669-023-09903-4.

Riedesel, L., Laidig, F., Hadasch, S., Rentel, D., Hackauf, B., Piepho, H.P., Feike, T., 2022. Breeding progress reduces carbon footprints of wheat and rye. J. Clean. Prod. 377, 134326. https://doi.org/10.1016/j.jclepro.2022.134326.

Shao, G., Zhou, J., Liu, B., Alharbi, S.A., Liu, E., Kuzyakov, Y., 2024. Carbon footprint of maize-wheat cropping system after 40-year fertilization. Sci. Total Environ. 926, 172082. https://doi.org/10.1016/j.scitotenv.2024.172082.

Shrestha, P., Karim, R.A., Sieverding, H.L., Archer, D.W., Kumar, S., Nleya, T., Stone, J.J., 2020. Life cycle assessment of wheat production and wheat-based crop rotations. J. Environ. Qual. 49 (6), 1515–1529. https://doi.org/10.1002/jeq2.20158.

Simmons, A.T., Murray, A., Brock, P.M., Grant, T., Cowie, A.L., Eady, S., Sharma, B., 2019. Life cycle inventories for the Australian grains sector. Crop Pasture Sci. 70 (7), 575–584. https://doi.org/10.1071/CP18412.

Soares, D.C., Bonfim-Silva, E.M., Silva, T.J.D., Anicésio, É.C., Duarte, T.F., Oliveira, J.R., 2023. Growth and production of wheat cultivars under water tensions in Cerrado soil. Rev. Bras. Eng. Agrícola Ambient. 27 (4), 279–286. https://doi.org/10.1590/1807-1929/agriambi.v27n4p279-286.

Statistica, 2024. Worldwide Production of Grain in 2023/24, by Type (In Million Metric Tons). https://www.statista.com/statistics/263977/world-grain-production-by-type/access. (Accessed 20 August 2024).

Tahmasebi, M., Feike, T., Soltani, A., Ramroudi, M., Ha, N., 2018. Trade-off between productivity and environmental sustainability in irrigated vs. rainfed wheat production in Iran. J. Clean. Prod. 174, 367–379. https://doi.org/10.1016/j.jclepro.2017.10.305.

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.

Tiecher, T., Gubiani, E., Santanna, M.A., Veloso, M.G., Calegari, A., Canalli, L.B., dos, S., Finckh, M.R., Caner, L., Rheinheimer, D. dos S., 2020. Effect of 26-years of soil tillage systems and winter cover crops on C and N stocks in a Southern Brazilian Oxisol. Rev. Bras. Cien. Solo 44, e0200029. https://doi.org/10.36783/18069657rbcs20200029.

United Nations (UN), 2024. Department of Economic and Social Affairs, Population Division. World Population Prospects 2024: Ten Key Messages. https://population.un.org/wpp/Publications/Files/WPP2024_KeyMessages.pdf. (Accessed 9 August 2024).

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.