Journal of Cleaner Production 467 (2024) 142963

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Are Geographical Indication products environmentally sound? The case of pears in North of Italy

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ARTICLE INFO

Handling Editor: Xin Tong

Keywords:
Geographical Indications
Environment
LCA
Life cycle assessment
Pear
Sustainability

ABSTRACT

The sustainability of Geographical Indication (GI) products has been investigated from social and economic standpoints, but their environmental sustainability is not yet well understood. This gap is especially problematic for food products because their production processes have significant impacts on the environment and at the same time are highly affected by climate change. This research is aimed to investigate the environmental performances of an Italian GI pear, by comparing its impacts with those of the corresponding conventional production, and to identify the most important improvement strategies. The case of "Pera Mantovana" is assessed through a life cycle assessment. Primary data are collected through extensive in-person interviews across a local sample of four on-field farms and two post-harvest organizations. The environmental impacts are not found to differ between GI and conventional productions. Moreover, the main hotspots are identified, and improvement strategies are evaluated. It is recommended to use the existing GI specification as a vehicle of environmental standards, also profiting from the new European regulation on GIs.

1. Introduction

Nowadays, almost one-third of overall GreenHouse Gas (GHG) emissions are generated by the agrifood sector (Ritchie et al., 2022). Increasing food system sustainability has become critical, not only due to the growing consumer, producer, and policymaker awareness (D'Ammaro et al., 2021), but also to meet Sustainable Development Goals (SDGs) and European objectives (European Commission, 2019), particularly those related to the Common Agricultural Policy (European Commission, 2022).

Food products with a Geographical Indication (GI) are important elements of the European agrifood sector and they are defined as "*names which identify products that originate in a specific place, whose quality or characteristics are attributable to their geographical origin*" (European Union, 2012). These products are diffused most in mediterranean countries, particularly in Italy (886 products), France (766 products), Spain (378 products) and Portugal (203 products). In Italy they account for 20% of the entire agrifood sector (ISMEA and Fondazione Qualivita, 2023). GI products can be Protected Designation of Origin (PDO) or Protected Geographical Indications (PGI), differentiating for the stronger link with their territory or origin. One important characteristic of these products is that producers must respect all the rules prescribed by the so-called specification. The specification contains the rules related to the area of production (in which territories the product can be made), the production process (e.g., how the product is made, specific plant layouts or phytosanitary practices) and the final product characteristics (e.g., shape, color, dimensions, nutrients). Rules written inside the specification are different for each GI product. They are written by the producers' organization and published by the European Union. GI producers are obliged to comply with these rules if they want to use the certification.

Recently a new European regulation on GIs has been approved (European Commission, 2024), also aimed at increasing the sustainability of these products. The new reform encourages producers' organizations to evaluate the environmental sustainability of the production and to introduce environmental criteria inside the specification. However, the relationship between GIs and sustainability is still to be fully understood. There is consensus on GIs' potential advantages for the social and economic aspects of sustainability. For instance, their higher pricing (European Commission, 2021) can increase the revenue for producers (FAO, 2009, 2018). From a social perspective, GIs can help preserve traditional knowledge while promoting cultural and culinary

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https://doi.org/10.1016/j.jclepro.2024.142963
Received 15 March 2024; Received in revised form 23 May 2024; Accepted 19 June 2024

heritage (Milano and Cazella, 2021), and enable the development of rural and peripheral regions (Belletti and Marescotti, 2011; Sgroi, 2021). Regarding environmental sustainability, there is no agreement on their role in relation to environment impacts (Falasco et al., 2024).

Since progress in current understanding of this topic may shed light on the role of GI products for sustainable development, the paper poses two research questions.

- Is the presence of a GI regulation associated to a greater environmental sustainability of the production process?
- Which improvements can be introduced in the GI specifications to enhance their environmental sustainability?

To reach these objectives an Italian GI product is selected as a case study (Pera Mantovana PGI). The impacts of Pera Mantovana PGI are assessed through a Life Cycle Assessment (LCA), and they are compared with the production of conventional pear in the same area (Pianura Padana area). Both GI and non-GI farms were selected in the same territory to have comparable weather and soil conditions across their locations. Indeed, the choice of a sample of geographically homogeneous cases is a necessary condition to identify the effects of GI production process net of major confounding factors (Cabot et al., 2022).

LCA can help in improving the sustainability of food production and consumption patterns, despite certain difficulties and problems arising from the application of life cycle thinking to food chains (Notarnicola et al., 2017). LCA is largely applied to the food sector, both to assess and to compare the environmental impacts. There are studies that have applied LCA to pear production. (Vatsanidou et al., 2020) evaluated the effect of the application of a variable rate fertilization in a pear orchard on the environmental impacts, while (Tamburini et al., 2015) focused on the evaluation of five mediterranean products including pears and (Figueiredo et al., 2013) focused his analysis on apples and pears, also including the storage and distribution phase. LCA is also used to evaluate the environmental impacts of GI products, as done by (Bava et al., 2018; González-García et al., 2013; Le Féon et al., 2023). However, in all these cases no comparison between conventional and GI products has been made. When the LCA is used to compare environmental impacts, it is largely applied to compare different product systems. E.g., in (Goossens et al., 2017; Verdi et al., 2022), LCA was used to compare organic and conventional production. To the authors' knowledge, no study has used LCA to compare the environmental impacts of GI and non-GI products. The only study aimed at comparing GI and non-GI is (Bellassen et al., 2022), but did not use LCA as a methodology. In their sample, certified food (organic and GIs) had better performances compared to non-certified food on most economic and social indicators, although their performances on main environmental indicators (carbon and water footprint) were comparable.

2. Method

This section can be traced back to the first two steps of an LCA: goal and scope and life cycle inventory.

2.1. Goal and scope

The first step of an LCA is the definition of the goal. Therefore, the aim of this study is to analyze the production of pears, comparing PGI and conventional farms and understand if the GI certification can be associated with lower environmental impacts and how sustainability can be improved.

When analyzing agrifood systems using the LCA, two Functional Unit (FU) are usually taken into consideration. Some papers use an area-based FU, such as hectares or square meters (Li et al., 2021; Mousavi et al., 2023) but the most common FU used in LCA applied to food is the mass-based FU (Cabot et al., 2022; Svanes et al., 2022), as done for example by (Mathis et al., 2022; Parrot et al., 2022). Therefore, in this study the chosen FU is 1 kg of pears. Then in Section 3.4.1 a sensitivity analysis is conducted to understand the impact of this choice on the results, comparing the chosen FU (kilogram) with hectares.

2.1.1. Description of the systems under study

As mentioned before, the GI sector is strategic for European mediterranean countries (e.g., Italy), where it is guided by a complex plot of tradition, innovation, and sustainability. Indeed, the relationship between territory and food production is particularly strong, as also shown by the massive use of GIs. The production of pear has been present in the North of Italy since many centuries (Sansavini, 2020). The planted area and quantities produced are tracked by ISTAT (*Istituto nazionale di STATistica – Italian National Institute of Statistics*) since 1936 and are reported on Fig. 1.

Three regions (Lombardy, Emilia-Romagna, and Veneto) located in North of Italy, more precisely in Pianura Padana, have covered the 76% of the total Italian pear production in 2022 (ISTAT, 2023). The importance of the pear supply chain for the territory is also testified by the introduction in 1998 of two geographical indications (GI) for pear, the Pera Mantovana PGI and Pera dell'Emilia Romagna PGI, which are the only two Italian pears bearing a geographical indication. In 2021, there were five producers of Pera Mantovana PGI, according to (Cavaliere, 2023).

As mentioned before, having a GI certification means that producers must respect the rules written in the specification, which for the Pera Mantovana PGI are summarized in Table 1. However, in this case, these constraints are so wide that they are also respected by most farms in the territory, whether they have the PGI certification or not.

The system under study is composed of six elements, named A, B, C, D, E and F, for anonymity reasons, located in the Pianura Padana territory. To have a complete view of the production processes of the pears, four pear producers (farms A, B, C and D) and two post-harvest firms (E and F) have been considered. E and F have been included since, as quite usual in the Italian agrifood sector, the producers of pears are different from the post-harvest operators. Usually, producers sell their product to cooperatives or to producers' organizations, which oversee transport, storage, processing, and sales of pears. Moreover, two benchmarks (Ribaudo Spindle and Ribaudo Palmette) were considered to verify the reliability of the elaborations and results. To calculate the two benchmarks, (Ribaudo, 2017) provided the data related to inputs and processes, which are referred to two different cultivation techniques, Spindle and Palmette, both present in the Pianura Padana area. The first is a cultivation system that involves specific pruning to achieve a cone or pyramid shape in the tree while the second involves shaping trees into a "palm' form, with branches growing horizontally from the main trunk. Both systems seek to improve fruit yield and quality, to make administration and harvesting operations easier, and to improve the tree's general health. The decision between spindle and palmette cultivation is determined by several factors, including pear type, soil, climate, and the farmer's preferences.

Fig. 2 shows the area of production of Pera Mantovana PGI, as well as the localization of the six interviewed farms and firms, while Table 2 shows the main details of each interviewed farm and of the benchmarks.

2.1.2. System boundaries

The system boundaries are from cradle to gate since the analysis covers phases from the production of all inputs to the post-harvest firm gate. For the field part, one single productive year was considered, excluding the non-productive and low-productive years (at the beginning and end of orchard life) since no reliable data were available to model these phases (see Section 2.1.3). The general production process can be summarized as in Fig. 3, however relevant differences between the cases will be briefly highlighted. None of the differences are strictly related to the GI specification, but to technological factors and farm management decisions. As mentioned before, the limitations found in the Pera Mantovana PGI specification are respected also by non-GI

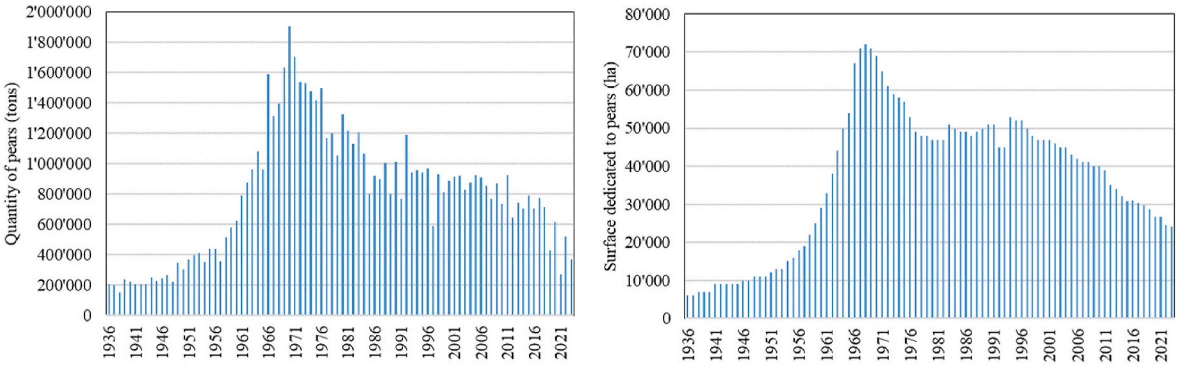

Fig. 1. Pear produced in tons and land in hectares from 1936 to 2023 in Italy.

Table 1
Rules written inside the Pera Mantovana PGI specification.

Origin	Selected municipalities in the province of Mantua, Lombardy
Cultivar	Abate Fetel, Conference, Decana del Comizio, Kaiser, Max Red Bartlett, William, Carmen e Santa Maria
Products characteristics	Color, shape, dimension, minimum content of sugar, hardness (which differ for every cultivar)
Production method	Planting pattern (6000 plants/ha) At least one pruning each year Integrated pest management or organic cultivation Maximum yield (55 t/ha)

producers (e.g., the maximum yield is limited by the specification at 55 t/ha, and all the farms are under this value).

The phases of planting and removal of the orchard as well as the orchard materials (cement, plastics, steel, …) were not considered. The nursery stage and the production of seeds were not considered as well due to the scarcity of primary and secondary data and since the nursery stage and planting also have a reduced contribution to the final emissions, as reported by (Vatsanidou et al., 2020). The remaining wood, after the removal of the orchard, was not considered since no clear information is available on its final use. However, if correctly managed, e.g., with recovery of energy, it could reduce energy and environmental impacts. The wood produced during the annual pruning of the orchard was also not included in the analysis. Farms A, B and D leave the wood in the field, after chopping, to exploit its soil improver power. In the other case (Farm C), wood is collected and used in private boilers, or it is collected by specialized companies. These phases were excluded due to lack of reliable information on the soil improvement power and the relative decrease in use of fertilizer or regarding the energy recovered when used for energy purposes.

The main differences between the interviewed farms in relation to the on-fields treatment of pears have been observed in the irrigation, fertilizers usage, mowing and weed management.

Irrigation. The farms use different systems: Farm C uses hose-reel irrigators powered by a diesel pump. Farm D used the drip irrigation system powered by a diesel pump. Farm A and B use sprinkler irrigators, but the first is powered by electricity from its photovoltaic (PV) system and the second by diesel. These differences have an impact on energy consumption and related emissions.

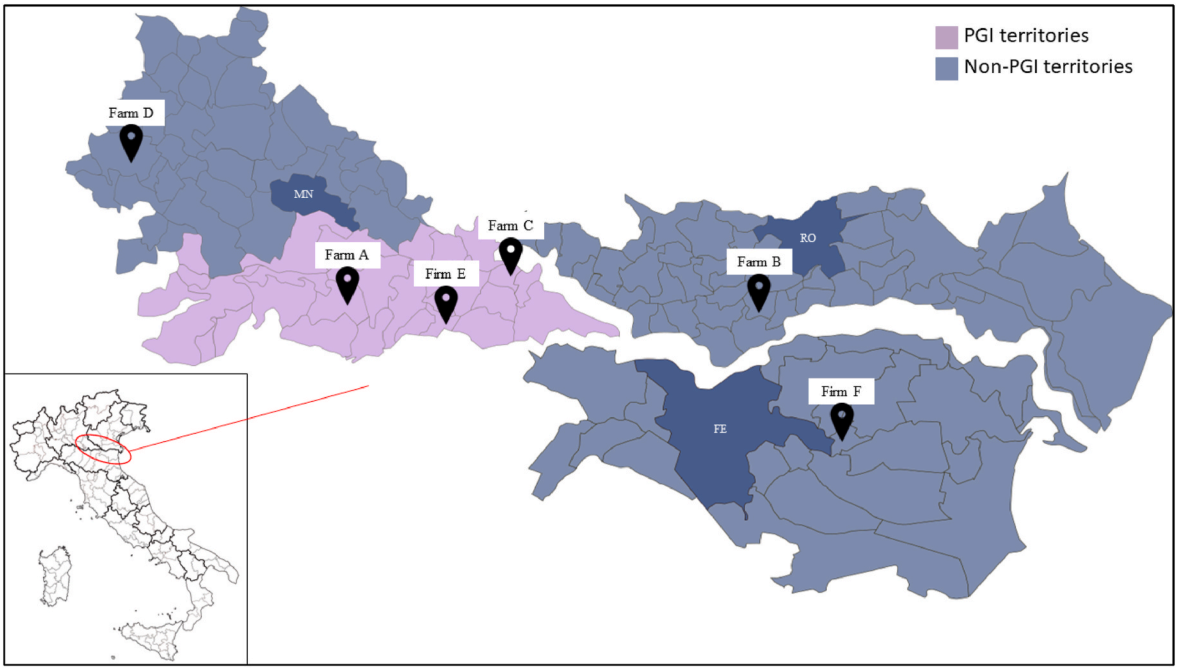

Fig. 2. Map of the territory where Pera Mantovana PGI can be produced (purple), along with the approximate location of the selected case studies. The darker blue areas are the areas where the regional capital is located. The three regions referrer to the Region Lombardy (top left), Region Emilia-Romagna (bottom, right) and Region Veneto (top right). (FE=Ferrara, MN = Mantova, RO=Rovigo). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Characteristics of interviewed farms and firms and of benchmarks.

	Farm A	Farm B	Farm C	Farm D	Ribaudo Spindle	Ribaudo, Palmette	Firm E	Firm F
Province	Mantova (MN)	Rovigo (RO)	Mantova (MN)	Mantova (MN)	–	–	Mantova (MN)	Ferrara (FE)
Phases covered	P	P	P	P	P	P	PH	PH
Hectares dedicated to pears cultivation (ha)	6	4.5	7	11	–	–	–	–
Yield (t/hayear)	14.7	16.7	12.9	18.2	35.0	33.0	–	–
Planting density (plant/ha)	2450	3150	3000	7500	2500	1250	–	–
kg/plant[a]	6.0	5.3	4.3	2.4	14.0	26.4	–	–
Pears/plant[b]	40	35	29	16	93	176	–	–
Quantity of pears handled each year (only for post-harvest)	–	–	–	–	–	–	6′500 t/year	10′000 t/year
Type of cultivation								
Conventional	X	X			X	X	X	X
Organic			X	X			X	X
PGI	X		X				X	X
Interviewee	Owner	Owner	Owner	Owner	Ribaudo (2017)	Ribaudo (2017)	President	Sales Manager

P = Production/PH = post-harvest.

[a] From the PGI specification the maximum value of kg/plants is 9.2 which means a maximum of 61 pears/plant.

[b] An average weight of 150 g/pear was used.

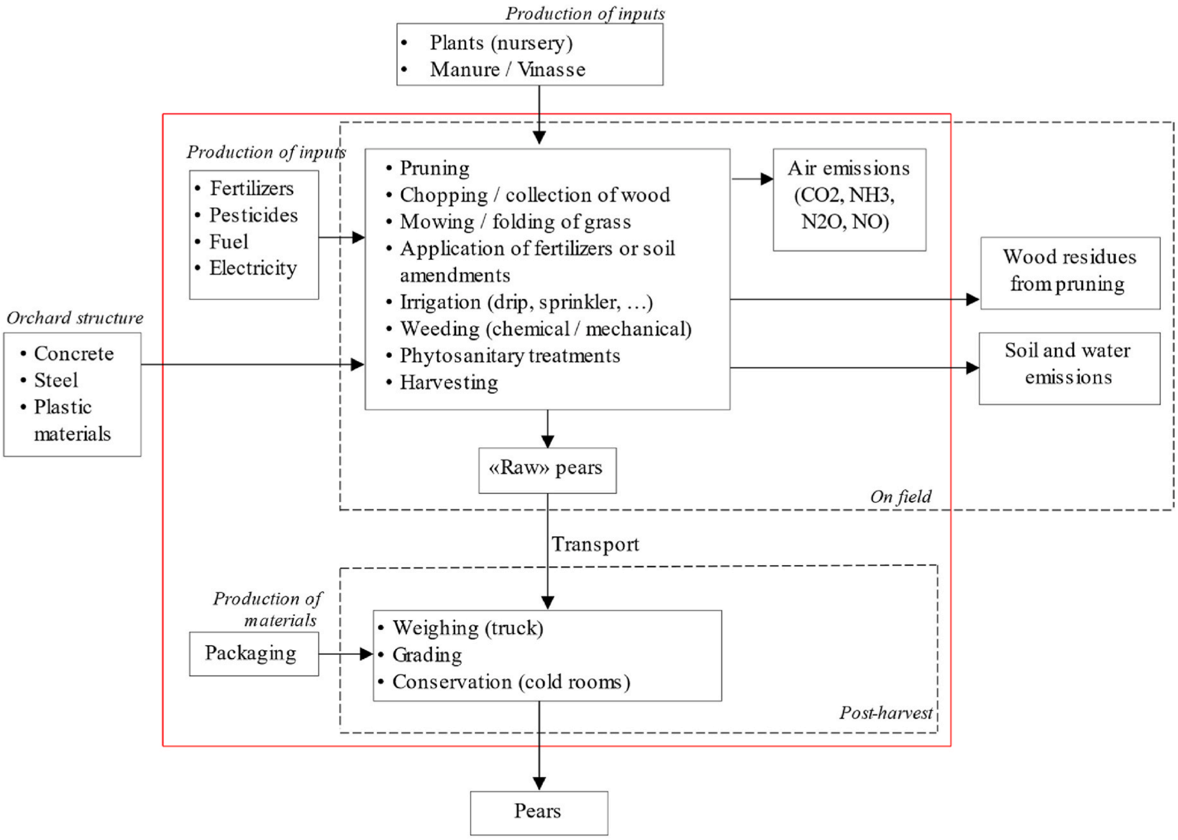

Fig. 3. Production processes of pears (The red lines indicate the system boundaries). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fertilizers use. Even if compliant with the current regulation, the quantity and type of fertilizers applied vary significantly between the farms. Especially in farm D, which uses only manure and beet vinasse and no chemical fertilizers, in contrast to all the other farms. Also, the application of fertilizers can sometimes be done partially or totally through the fertigation system, rather than with spreaders (e.g., Farm A, Ribaudo Spindle).

Mowing. Farm D is the only farm which does not mow the field, but instead does a folding of grass. This practice creates a natural mulch, which is useful to hold more water and to improve soil fertility (*From farm D interview*). Yet the machinery to complete this operation is the same machine used for mowing but without the cutting blade, therefore the machinery and its consumption are identical.

Weeding. The process of weeding can be done mechanically or chemically. Farm A and the two benchmarks (Ribaudo Spindle and Ribaudo Palmette) use glyphosate to make a chemical weeding. Farms B, C and D make a mechanical weeding, without using glyphosate.

2.1.3. Main assumptions

Based on the available information, some assumptions regarding the harvest features are needed to accomplish the elaborations. Assumptions regarding the yields, the orchard life, the use of pesticides, the irrigation and the post-harvest phase were made.

Yield and plant density. As shown in Table 1, there is a high variability in terms of yield, that can be due to differences in the production system, differences in the quantity of inputs used or differences in the planting density (Table 1). Moreover, there are substantial differences between the number of pears produced by the analyzed farms and the benchmarks. This can be explained since the benchmarks refer to a period where the pears in North of Italy were facing a better situation compared to 2023 (year of data collection) in which the pear cultivation sector is facing a huge crisis. In fact, in recent years (after 2018) the appearance of new insects and diseases as well as the impacts of climate change, changes in chemicals regulations and a sharp rise of agricultural inputs cost, have been challenging the sector of pear production, especially in Italy. The last consideration about yield is that the value declared by the farms refers to all the pears that are taken from the plants. Yet this is not a complete indicator, since each year farmers harvest superior quality pears destined for fresh consumption but also pears intended for the agrifood industry (for wrong dimension, aesthetics defects, diseases). This means that farms with a high yield do not necessarily produce a higher number of good-quality pears. For example, Farm A has declared in 2022 a production of 88.2 tons of pears, of which 35.6 tons (40%) are intended to transformation industry. For this study, the considered products are all the pears harvested, assuming that all pears are intended for fresh consumption. It can also happen that some low-quality pears are not harvested (food loss), and this is usually accounted for with differences found in the yields.

Orchard life. Moving to the orchard life, all farmers confirmed that the orchard life is variable, depending on many factors such as the quality of the plant and of nursery stage, quantities of fertilizers and phytosanitary products, quality of the soil, climate, and others. Due to this variability, a medium value of twenty years was used for all the farms. Moreover, three periods can be individuated during the lifetime of a tree:

- A period without production, corresponding to the first years after the planting of orchard.
- A period with reduced production, which can be found at the beginning of the orchard lifetime (two to five years) and at the end of the orchard lifetime (one to two years).
- A period with full production (FP). In the FP, the yield can vary from year to year, based on many factors (e.g., climate, fertilizers, diseases, …).

No complete data were available for the periods of no production and of reduced production, therefore only the FP period was considered in this study.

Pesticide use. Unfortunately, primary data related to pesticides were available only for farm D. Even regional databases do not contain sufficient information. Therefore, the average value (30.4 kg/ha) of parameters found in literature (studies are reported in Table 8) was used. Moreover, in the Agribalyse database, there are no organic pesticides or components, so the “generic pesticides” voice was used, both in organic and conventional farms.

Irrigation. Different systems have been found. Farm A uses electric pumps for irrigation, with electricity coming from a PV system, unlike all the other farms that use pumps fueled by diesel. The electricity used for irrigation by farm A is around 10% of the total electricity produced by the PV system, while the rest (90%) is sold to the national network according to the current regulation and exchange mechanism. Yet this energy sold is not accounted for in the LCA model, even if it could reduce the impact of the farm. Moreover, for Farm C, water consumption was not available from primary data. The water used was then estimated as the difference between the water needs reported in (Regione Lombardia, 2023a), and the quantity of rain recorded in the weather data of the station of Sermide (MN)[1] in relation to the months from May to September of 2022.

Post-harvest operations. This phase was considered in terms of energy and environmental impacts related to the operation (cool storage, packaging, and transport). The production process of the components such as machinery and cold rooms were not considered. For the operation, the total energy consumption for storing the pears was estimated based on the total energy consumption of the firm. Of course, the energy consumption for storing in cold rooms depends on local climate, mass of pears, market demand, and marketing choices. For packaging, the firms reported the use of cardboard boxes, wood boxes and plastic bins. Cardboard boxes are single-use packaging, while the wood boxes and plastic bins are returned. Firm F uses also single-use plastic boxes. In the evaluations, a lifetime of 5 years for wood boxes and of 10 years for plastic bins was considered. To calculate the quantities of materials for packaging, a medium pear with weight equal to 150 g and volume equal to 18.75 cl (0.0001875 m^3) was considered. The impacts due to the transportation from producing farms to the post-harvest cooperatives were accounted in the post-harvest stage, based on the average distance that the two firms have declared.

2.1.4. Indicators and data elaboration

Considering the decarbonization objectives of the European Union, reaching a climate-neutral system by 2050 (European Commission, 2019), the chosen indicators are Global Warming Potential (GWP) and the Cumulative Energy Demand (CED). Since water scarcity is also an issue, water use was calculated only in relation to the on-field irrigation due to data availability. The data gathered during the surveys were initially collected in an Excel file. Then, they were analyzed using openLCA v 2.0[2] choosing the database Agribalyse V3.0.1.

For GWP impacts were estimated using the method proposed by (IPCC et al., 2021). For fertilizers’ emissions in air, NH_3, N_2O, NO and CO_2 were considered as pollutants as it follows. According to (Koch and Salou, 2015), NH_3 emissions for orchards are only connected to the use of mineral and organic fertilizers. These emissions are influenced by soil, climatic, and microbiological conditions as well as the type of fertilizer used or the type of excretion. Accordingly, values in (Koch and Salou, 2015) were used for NH_3, CO_2 and NO emissions while values in (Nemecek and Kägi, 2007) were used for N_2O emissions since the method by (Koch and Salou, 2015) requires data that were not available.

2.1.5. Definition of scenarios of improvement and of sensitivity analysis

Firstly, a sensitivity analysis was conducted on the FU. Sensitivity analysis is a process for determining how specific choices on data and techniques may affect a study’s conclusion. This analysis is necessary to insulate the influence of the chosen FU, since in literature both kilograms and hectares are used for the LCA of agricultural products.

Through LCA the processes that contribute the most to impacts, namely the hotspots, can be identified. Regarding these issues, this research evaluates the impacts of possible improvement scenarios, which could possibly be introduced inside the GI specification. According to primary data and further information collected during the surveys, attention was paid to irrigation and fertilization. This is coherent with their significance in total impacts, with the identified priorities in decarbonization of agriculture (European Commission, 2019) and more generally a more extensive and sustainable production pattern (European Commission, 2020). In fact, irrigation and the use of fertilizers are the most impactful phases for all interviewed farms, as confirmed also by (Cabot et al., 2022). By contrast, the use of pesticides was not considered, even if it is one of the main contributors to the final

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[1] https://www.codima.info/stazione-008.

[2] https://openlca.org.

impacts, due to the unreliability of data, which could only be estimated by secondary sources.

The first scenario is related to irrigation. For this scenario two steps were defined: firstly, a shift from oil to electric pumps and secondly assuming the use of renewable electricity from PV. The first step was applied to farms B, C and D which use oil pumps for irrigation, considering the ratio of kWh of electricity per m^3 of irrigated water obtained by farm A which already uses electric pumps. The electricity needed for irrigation was then estimated proportionally, based on the water consumption declared by the farms and assuming the Italian grid and energy mix. The second stage was applied to farms B, C and D and benchmarks, assuming electricity produced by PV instead of bought from the Italian grid. Farm A, instead, already uses PV electricity for irrigation, and therefore has not been optimized.

The second scenario is related to the fertilizers' use to understand how a reduction in the use of fertilizers can reduce the final impacts. As a first evaluation, the use of fertilizers was reduced by 50% according to (Vatsanidou et al., 2020). With the application of variable rate application method, a basic technique of precision agriculture, they have estimated the possibility of maintaining the yield due to better fertilizer use efficiency on different crops, including pears (Vatsanidou et al., 2020). For this reason, the amount of nitrogen used was reduced by 50% as well as the related processes:

- The process of "Application of fertilizer" was reduced by 50%, assuming that the time of application is proportional to the quantity of fertilizers adopted.
- The impact of transporting the fertilizer was halved.
- The direct emissions from fertilizers were halved.

It must be underlined that the adoption of such agronomic techniques implies new precise management systems and appliances whose impacts are not considered in the analysis here presented.

The last scenario is related to the post-harvest phase, due to the wide range of variability of management, the only reliable option was to assume that the electricity needed for the cold storage was produced by PV. Since firm E already has 50% of electricity produced by PV, as first optimization, the same was assumed for firm F. Then as a second optimization it was assumed that the 100% of the electricity for cooling the pears is produced by PV for both firms (E and F).

2.2. Life cycle inventory

This phase of the LCA involves the data collection and the calculation procedure for the quantification of inputs and outputs of the studied system. In this case, inputs and outputs concern energy, raw materials and other physical inputs, and emissions to air.

2.2.1. Data collection

The analysis uses primary data, collected with structured surveys, semi-structured interviews, and direct observation, during on-site visits to the firms. After the visits, each respondent was interviewed with semi-structured interviews (approximately 1 h long) regarding the pear value chain and its production process. The purpose of these initial interviews was to collect information on the farm and on their specific production process, to identify similarities or differences that could affect the results. The interview was divided into three parts: a) information about the firm and its history; b) information about the production process; c) information about the GI mark and its operation.

Right after the interview, a survey was proposed with the aim of collecting the primary data regarding the inputs and the production processes necessary to perform the LCA. Also in this case, two sections were present: Data regarding the inputs used (e.g., fertilizers and pesticides) and data regarding the processes needed to cultivate pears and relative fuel requirements. The same data were asked for the productive years as well as for the non-productive years and low productive years. Unfortunately, none of the firms was able to provide data related to the non-productive and low-productive years. The interviews and survey were conducted in Italian, between February and April 2023 and the text used is available inside the Supplementary Materials.

2.2.2. Data quality

Nevertheless, primary data were not sufficiently complete to perform the full analysis. Integration with secondary data was therefore needed. To perform this, the scheme proposed in Fig. 4 was followed, privileging the use of primary data.

If primary data were not available, some datasets (Regione Lombardia, 2023a, Regione Lombardia, 2023b) of the reference first-level administrative division were chosen. The choice of regional dataset was done to obtain data referred to the territory and period of analysis. In case also regional data were not available, the data were taken from the scientific literature treating the pears production (list of paper in Table 8). In case data were not available in the literature, the Agribalyse database was used. This choice can impact the final results, since the Agribalyse information is not related to the regional context. There is the need to create regional inventories and impact assessment methods to strengthen the LCA methodology toward more regionalized analysis (Cabot et al., 2022).

2.2.3. Summary of collected data

Table 3 reports the final input data for the on-field phase, while Table 4 reports the input data for the two post-harvest firms.

3. Results and discussion

This section can be traced back to the last two phases of LCA: the life cycle impact assessment and the interpretation of results. Three main indicators have been selected to investigate relevant environmental issues such as decarbonization (by GWP and CED) and water consumption. In the following, results are grouped by on-field (Section 3.1) and post-harvest (3.2) activities. Then the hotspot of the production (Section 3.3) and some scenarios for improvements are presented (Section 3.4). Lastly the impacts of the average pear are shown (Section 3.5) and compared to literature findings (Section 3.6).

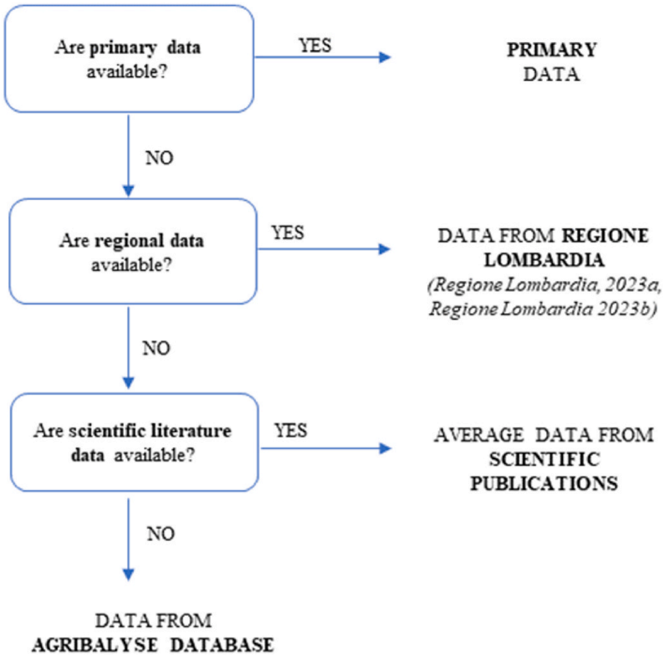
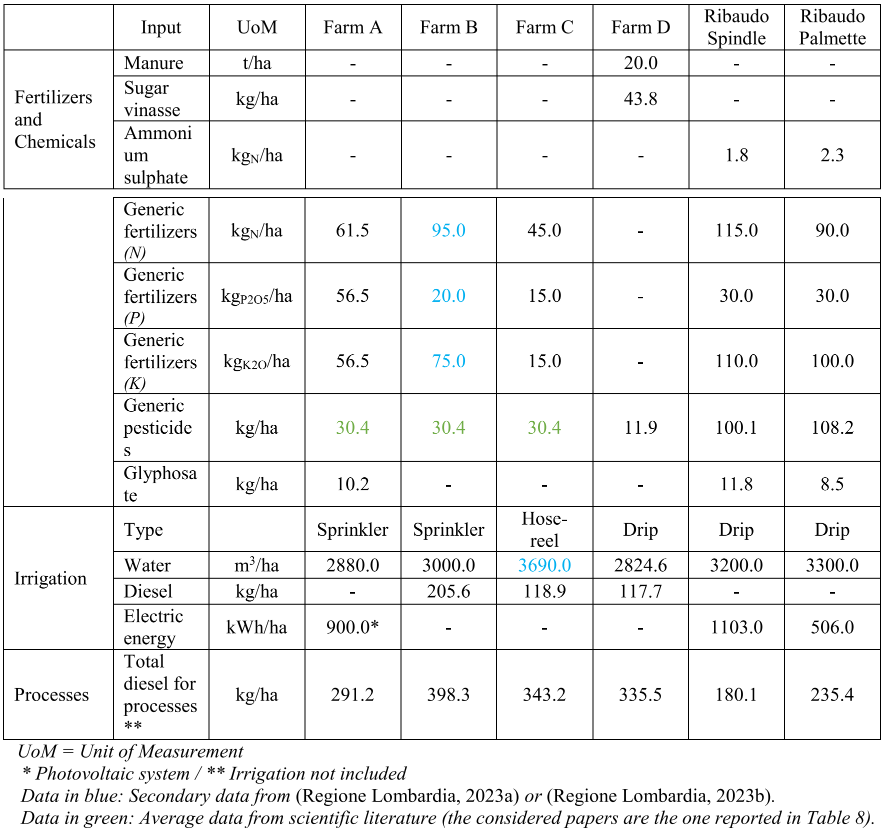


Fig. 4. Data source selection process.

Table 3
Inputs of the four production cases and benchmarks.



	Input	UoM	Farm A	Farm B	Farm C	Farm D	Ribaudo Spindle	Ribaudo Palmette
Fertilizers and Chemicals	Manure	t/ha	-	-	-	20.0	-	-
	Sugar vinasse	kg/ha	-	-	-	43.8	-	-
	Ammonium sulphate	kg_N/ha	-	-	-	-	1.8	2.3
	Generic fertilizers *(N)*	kg_N/ha	61.5	95.0	45.0	-	115.0	90.0
	Generic fertilizers *(P)*	kg_{P2O5}/ha	56.5	20.0	15.0	-	30.0	30.0
	Generic fertilizers *(K)*	kg_{K2O}/ha	56.5	75.0	15.0	-	110.0	100.0
	Generic pesticides	kg/ha	30.4	30.4	30.4	11.9	100.1	108.2
	Glyphosate	kg/ha	10.2	-	-	-	11.8	8.5
Irrigation	Type		Sprinkler	Sprinkler	Hose-reel	Drip	Drip	Drip
	Water	m^3/ha	2880.0	3000.0	3690.0	2824.6	3200.0	3300.0
	Diesel	kg/ha	-	205.6	118.9	117.7	-	-
	Electric energy	kWh/ha	900.0*	-	-	-	1103.0	506.0
Processes	Total diesel for processes **	kg/ha	291.2	398.3	343.2	335.5	180.1	235.4

UoM = Unit of Measurement
** Photovoltaic system / ** Irrigation not included*
Data in blue: Secondary data from (Regione Lombardia, 2023a) *or* (Regione Lombardia, 2023b).
Data in green: Average data from scientific literature (the considered papers are the one reported in Table 8).

UoM = Unit of Measurement.
Data in blue: Secondary data from (Regione Lombardia, 2023a) or (Regione Lombardia, 2023b).
Data in green: Average data from scientific literature (the considered papers are the one reported in Table 8).
* Photovoltaic system.
** Irrigation not included.

Table 4
Data inventory for post-harvest firms.

	UoM	Firm E	Firm F
Pears treated	t/year	6′500	10′000
Medium distance of producers	km	100	50
Cold rooms	m^3/cold room	1′100	1′100
	Number cold rooms	37	40
Packaging			
Wood boxes[a]	%	15%	30%
	Number	36′164	111′272
	dm^3/box	4.13	4.13
Carton boxes	%	2%	30%
	Number	7500	235′305
	g/box	300	550
Plastics bins[b]	%	83%	40%
	Number of bins	9′850	7′273
	kg/bins	30	30
Total energy[c]	kWh/year	890′000	1′000′000

[a] A lifetime of 5 years was hypothesized/The manufacturing process of wood was not considered.
[b] A lifetime of 10 years was hypothesized.
[c] Covers the consumption of cold room and other machinery. Firm E has 50% of energy from photovoltaic systems.

3.1. On-field results

The results related to the activities on-field are described in terms of GWP, CED and water consumption, based on the production of 1 kg of pears.

3.1.1. Global Warming Potential

The results of GWP are reported in Fig. 5, revealing that the production of pears creates emissions of 0.19 kg CO_2eq. per kilogram of pears, on average.

Benchmarks (grey bars) have significantly lower values compared to the analyzed cases. This can be explained by the much higher yields (about 34 t/ha instead of the average value of 16 t/ha provided by the

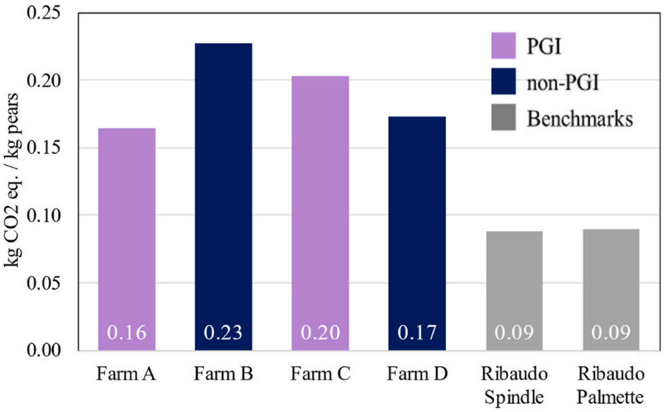


Fig. 5. GWP values expressed in kg CO2 eq./kg of pears.

farms involved). No significant difference can be noted comparing PGI production (purple bars) to conventional production (dark blue bars). In fact, the average GWP is 0.18 kg CO_2 eq./kg of pears for PGI compared to 0.20 kg CO_2 eq./kg of pears for conventional.

3.1.2. Cumulative Energy Demand

The results of CED are reported in Fig. 6, reveling that the production of pears implies the consumption of 2.33 MJ per kilogram of pears, underlining the same trend of GWP and the same considerations about the values represented by the grey, purple, and dark blue bars. The average CED value for PGI is 2.31 MJ, while for conventional CED is 2.36 MJ.

3.1.3. Water consumption

Water consumption refers only to the water needed for irrigation. These results are expressed in m^3 per kilogram, as reported in Fig. 7. Also in this case, purple bars refer to PGI farms, dark blue bars to conventional farms and grey bars to the benchmarks.

Also in this case, no differences can be detected between PGI and conventional production while the impact of yield on results is again considerably high. Farm C can be considered as an outlier since the values are higher than the others. This can be since water consumption of farm C came from secondary sources while the water consumption of the other three farms is taken from primary data. To have a better understanding of the quantity of water used, these results are expressed in terms of l/pear, considering an average pear of 150 g. On average pear production requires 25 l for each pear (Fig. 8).

3.1.4. Summary of on-field results

A summary of on-field results is shown through Fig. 9 by radar graphs. Four indicators (GWP, CED, water consumption and yield) are represented and values are normalized as ratio with the maximum value. The results are aggregated to compare PGI to non-PGI to detect the different performances.

No significant differences can be observed between PGI and non-PGI products, which can be explained from the absence of significant differences between the production of PGI pears compared to conventional ones, at the moment. LCA has shown that current PGI specification of production process is not sufficient per se to induce a greater environmental sustainability in the production of North Italy pears. An innovative use of LCA could be devoted to understanding where the production processes can be improved. Modifying the specification introducing environmental improvements could bring a change in the production process resulting in a more effective and focused use of the GI mark.

3.2. Post-harvest results

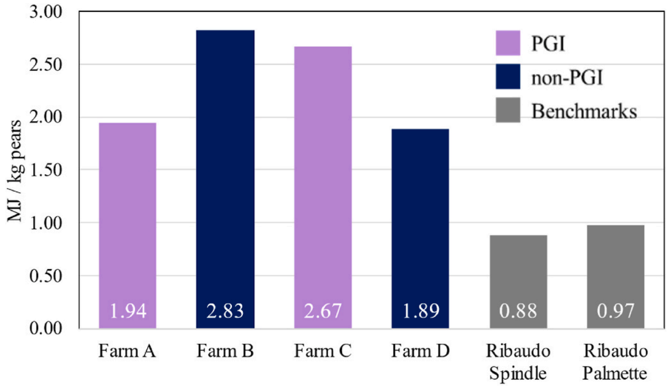


Fig. 6. CED values expressed in MJ/kg of pears.

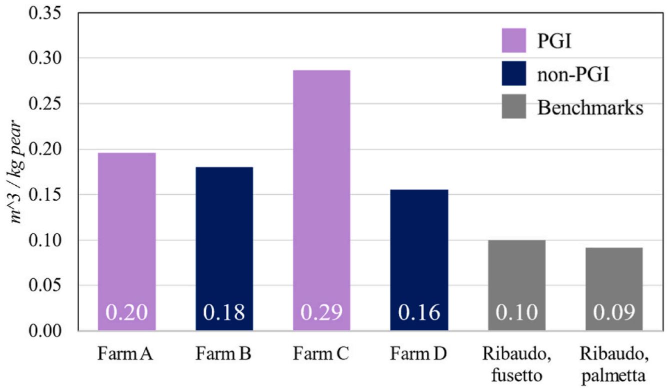


Fig. 7. Water values expressed m^3/kg of pears.

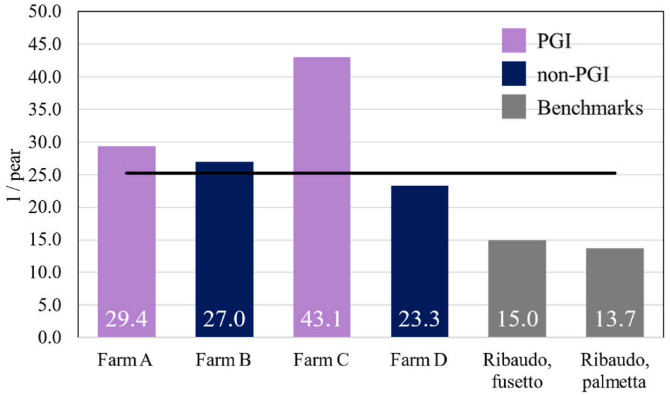


Fig. 8. Water consumption values in L/pear. The line corresponds to the average value.

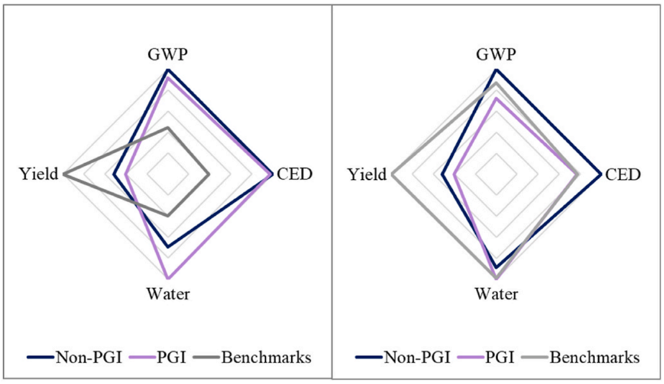


Fig. 9. Summary of results, comparing PGI and non-PGI Results are represented using as FU the kilograms (right) and the hectares (left).

As explained in Section 2, also two post-harvest firms participated in the study, since it is rare that producers also take care of these processes. For this stage only GWP and CED were evaluated.

On average it can be said that that the post-harvest phase of the pears production emits 0.063 kg CO_2 eq./kg pears and requires 0.76 MJ/kg pears.

From Fig. 10 it can be noticed that for both indicators, GWP and CED, firm E has a slightly better result compared to firm F. This can be due to the use of PV energy for the 50% in firm E and to the use of more reusable packaging. In fact, firm E uses 98% reusable packaging (wood boxes and plastic bins), while firm F uses only 70%, influencing the final impacts. The high amount of reusable packaging is also due to the final destination of the pears since firm E works only with markets and not

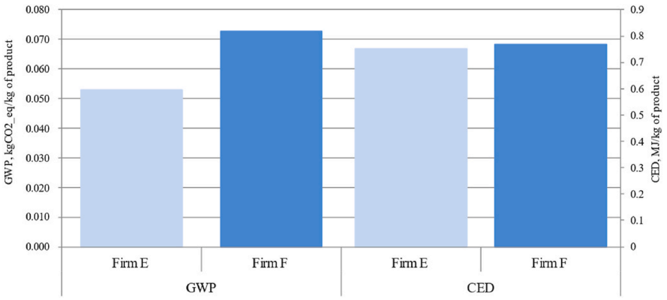


Fig. 10. Results for GWP (on the left) and CED (on the right) of post-harvest phase.

with large-scale retailers.

3.3. *Main hotspots*

As explained in Section 2.1.5, hotspots are the process that contributes the most to the final impacts. For the individuation of hotspots, only the impact in relation to the GWP values were analyzed. Starting from the on-field phase, the results are shown in Fig. 11.

The phases of input production and processes are comparable in almost all cases. The first difference is between the interviewed firms and the benchmarks, since for the first ones the processes' impacts are higher than the impacts related to the production of inputs, while for the second ones, it is the other way around. This can be due to a higher quantity of fertilizers and pesticides used by (Ribaudo, 2017), compared to the analyzed farms. Looking closely at the input phase the results show that in all six cases the emissions from fertilizers application and the production of pesticides are the two most impactful categories. On average these two categories are responsible for 73% of the impacts related to the inputs. Looking instead at the processes, four out of six cases report as the most impactful process the application of phytosanitary products constituting on average 37% of the processes' impacts. For Farm B, irrigation is the most impactful process. For farm D, the phytosanitary treatments are not the main contributor on the final impacts, due to the farm's reduced use of pesticides instead, pruning has the highest impact. This can be explained by the much higher density of plants per hectare.

Fig. 12 shows instead the results per phase relative to the post-harvest phase, for which three components have been identified: transportation of the raw pears (from the harvesting place to the post-harvest firm), packaging (wood, cardboard, and plastic packaging) and energy (for cold room and machineries).

For both, the firm's energy is the main contributor to GWP, mainly due to cold rooms. It must be noted that Firm E has half of its energy coming from a PV (in absolute values, the energy GWPs are 0.033 and 0.041 kg CO_2 eq./kg_{PEAR} respectively for Firm E and F). Transportation impacts of Firm E are higher due to the higher average distance covered to collect the pears. Instead, Firm F has higher packaging impacts since 60% of their production is sold to the GDO, usually in small non-reusable packages. Firm E instead is used to sell 98% of the pears production in reusable big plastic bins or wood boxes to big markets.

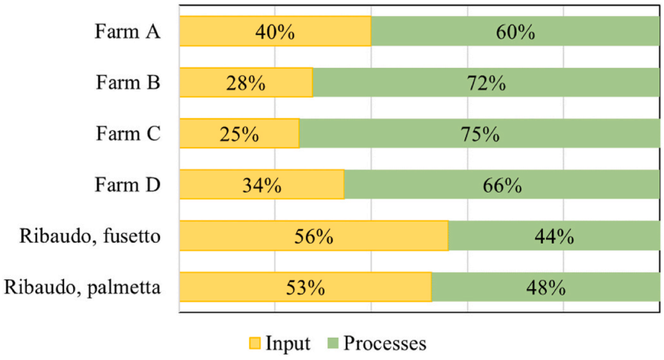


Fig. 11. Division of GWP values between phases for on-field step.

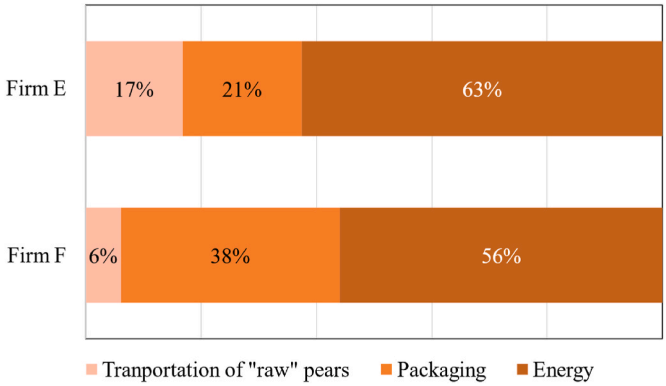


Fig. 12. Division of GWP values between phases for post-harvest step.

3.4. *Improved scenarios*

As described in Section 2 further analysis were made to understand the impact of changing the FU. Then two possible improvement scenarios have been analyzed for the on-field phase while one for the post-harvest phase. Since on-field fertilizers and irrigation are major contributors to total GWP, improvements have been focused on these topics.

3.4.1. *Analysis for FU*

This sensitivity analysis is needed since when applying LCA to an agrifood system, both the FU of kilogram of products and hectare are currently used in literature, without a clear preference toward one or the other. In this research the reference FU is kilogram of pears. Figs. 13–15 shows the elaborated impacts expressed for the two FU (kg and ha, respectively). In general, impacts per hectare reveal a wider variance than those per kilogram and this is because of the different yields. In fact, when kg is the FU, the representation shows the farm with higher yields (Ribaudo Spindle and Ribaudo Palmette) as the least impacting. But when using the hectares as FU, the differences between the impacts of the different firms are lower.

3.4.2. *Low carbon irrigation*

In this section a scenario based on improved irrigation techniques is described. This is made in two phases. The first one implies the change in the irrigation system from oil pumps to electric pumps. Farm A and the two benchmarks already had an electric powered pump, so they were

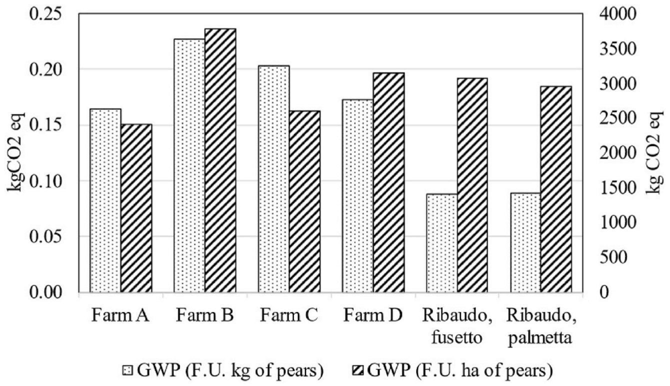


Fig. 13. GWP values expressed with two different FU.

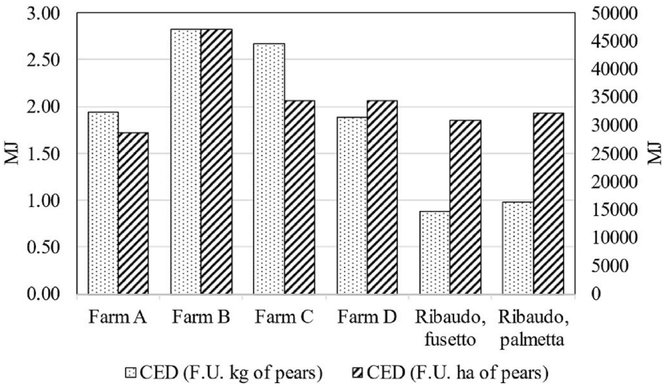


Fig. 14. GWP values expressed with two different FU.

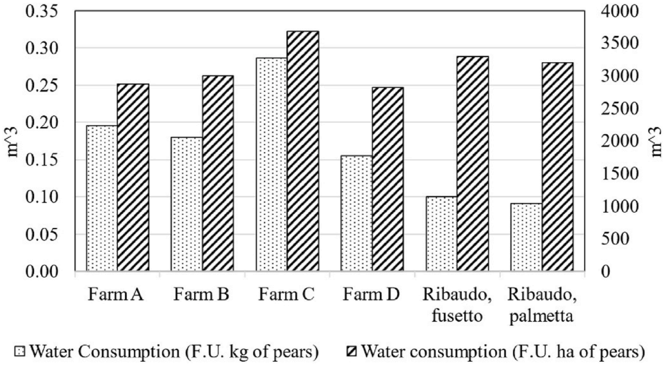


Fig. 15. Water consumption values expressed with two different FU.

not included in this scenario.

As shown by Table 5, the introduction of an electric pump can reduce both the GWP and CED of production by respectively 4% and 13% on average. The only case where the GWP value has increased is in Farm C, yet since the conversion to electric pump from diesel pump was made based on the m^3 of water used, the higher use of water of farm C could be the reason for this result. The second phase of improvement implies the adoption of a photovoltaic system instead of the national Italian mix as source of electricity. In this case the decrease in GWP and CED values compared to the baseline scenario are respectively 12% and 13% on average. However, this analysis has not considered the possible surplus energy generated by the photovoltaic system, which could decrease the impacts even more.

Moreover, this scenario is based only on the environmental side and therefore does not consider the economic cost of changing the irrigation system or implementing a photovoltaic system, which can have a high influence on the choice of farmers.

3.4.3. Lower rate of fertilization

In this case a reduction of 50% in the nitrogen applied was assessed, with no changes in the yield (Table 6).

The reduction of 50% of N applied brought a reduction of 13% for GWP values and 7% for CED values. Analogous results are obtained by (Denora et al., 2023), which evaluated, for the Mediterranean context, the application of the variable rate technology to wheat cultivation, obtaining as results an environmental benefit of 12–13%.

Therefore, investing in precision agriculture methods, such as the one proposed by (Vatsanidou et al., 2020), could be a way to reduce the impacts of pears production. In this case no direct investment is needed from the farmer. Yet an investment in capacity building, appliances, tools, and instruction of the farmer are necessary to apply this kind of agricultural practice. Also, a deeper understanding of the impact that the application of variable rate fertilization has on yield is needed, before possibly including this optimization inside the specification.

3.4.4. Photovoltaic systems in post-harvest firms

Energy saving along with the reduction of fruit waste are critical issues, as discussed in (Duan et al., 2020). In detail, they assessed that, as the energy consumption increases with increasing demands of fruit and vegetable to be refrigerated, more efficient appliances and techniques as well as refrigerants without negative effects on climate change should be employed. They added also that new thermodynamic cycles combined with different refrigerants and renewable energy sources should be proposed for efficient process integration. In addition, the use of phase change materials, such as the room wall for precooling and cold storage, is also a novel technical idea to achieve energy conservation and operation cost savings. So, they concluded that novel and improved equipment may also reduce energy consumption and increase energy efficiency.

In the present research, for post-harvest stages, a scenario improving electricity use was also developed since it is the major contributor to the final impacts. Unfortunately, due to lack of data about the storage systems (envelope, machinery, refrigerators, …) it was not possible to elaborate energy efficiency scenarios. Therefore, aware of the strong simplification, the improvement scenario introduces only the use of PV electricity, assumed equal to 50% as a first step of the scenario and to 100% as a second step (Table 7). Firm E already has 50% of energy coming from photovoltaic sources, so no changes were made in the first step of the scenario. Installing a PV system can therefore have a significant impact on the final values of GWP and CED for post-harvest firms. Combining this kind of intervention with measures of energy efficiency such as more efficient appliances is expected to magnify the results. However, as already discussed in section 2.5.1, no economic evaluation has been conducted, while these interventions imply investments by the firms.

According to (Ikram et al., 2021), the integration of PV or hybrid solar systems for refrigeration of cold storage facility is promising. They simulated an optimized system with reduced consumption and integration of a solar PV field demonstrating a high economic feasibility with the payback period of 5.2 years. So, they concluded providing recommendations for repowering along with renewable integration of cold storage facilities.

For the post-harvest phase, the integration of PV in case studies may result in a decrease of 44% of GWP and 33% of CED. Another way to reduce the impact related to the post-harvest stage is the reduction of the time of conservation, which would result in a reduction of energy used. This can be achieved also by promoting the consumption of seasonal products.

Table 5
Results of energy scenario.

			Avg.	Farm A	Farm B	Farm C	Farm D	Ribaudo Spindle	Ribaudo Palmette
I° step	% of reduction (GWP)	kg CO_2 eq./ha	−4%	–	−11%	+1%	−3%	–	–
	% of reduction[a] (CED)	MJ/ha	−13%	–	−19%	−8%	−11%	–	–
II° step	% of reduction (GWP)	kg CO_2 eq./ha	−12%	–	−20%	−13%	−13%	−12%	−6%
	% of reduction[a] (CED)	MJ/ha	−13%	–	−25%	−18%	−19%	−11%	−5%

[a] *Compared to baseline scenario.*

Table 6
Results of fertilizer scenario.

		Avg.	Farm A	Farm B	Farm C	Farm D	Ribaudo Spindle	Ribaudo Palmette
% of reduction[a] (GWP)	kg CO_2 eq./ha	−13%	−13%	−11%	−7%	−18%	−16%	−14%
% of reduction[a] (CED)	MJ/ha	−7%	−9%	−5%	−3%	−7%	−9%	−8%

[a] *Compared to baseline scenario.*

Table 7
Results of post-harvest scenario.

	Firm E		Firm F	
	GWP	CED	GWP	CED
Baseline scenario	0.05	0.75	0.07	0.77
Scenario 50%	0.05	0.75	0.05	0.75
Variation[a]	–	–	−23%	−19%
Scenario 100%	0.03	0.55	0.04	0.47
Variation[a]	**−43%**	**−27%**	**−45%**	**−39%**

GWP expressed in kg CO2 eq./kg $_{\text{PEARS}}$ and CED expressed in MJ/kg $_{\text{PEARS}}$.
[a] Compared to baseline scenario.

3.5. *Mean results for the pear supply chains*

To summarize the results, the mean values of the obtained GWP quantities of the six analyzed elements have been calculated, excluding benchmarks. The results are shown in Fig. 16, revealing a total GWP of 0.25 kg CO_2 eq./kg pears. The most critical aspects for the pears production are represented by fertilizers and pesticides use and production and from irrigation. The research should continue to focus on these aspects since they bring great opportunities for improvement.

3.6. *Comparison with literature*

To obtain a validation of the results, they were compared with results found in literature, as reported in Table 8. One of the main limitations of LCA is comparability since each paper can adopt different assumptions and different system boundaries. Considering this, the system boundaries adopted by each paper have been mapped, to give a clear idea of the phases that have been considered.

As shown by Table 8, the only indicator which is mapped in all the studies found is the GWP, while for other indicators, only few studies have reported them. For GWP, the results of this research are compatible with the ones found in literature, especially considering the differences in the definition of the system boundaries.

4. Conclusion

GI products originate from the willingness to strengthen the social and economic benefits of production processes on origin communities, but their contribution to sustainable development critically depends also on their environmental performance. This paper demonstrates that the application of LCA to the production process of a GI agricultural product, along with the identification of hotspots in such process, is suitable for addressing the understudied question on sustainability of GI production processes. In detail, the paper answered the two research questions on the environmental sustainability of GIs, using North Italy GI pears as case study, identifying the possible improvements for this specific production process.

As a general finding, GI mark was not originally created to pursue environmental sustainability and therefore in our cases few or no references to environmental sustainability are made inside the specification. Therefore, currently, no differences in environmental sustainability, attributable to the GI certification, can be observed between GI and non-GI producers. Indeed, GI products can leverage the advantage of a unique scheme that contains GI rules and additional environmental standards. Modifying and expanding this existing mark, integrating the economic and social aspects with the environmental ones may be more effective than creating a new mark that could confuse the consumers. A wise writing of the specification, making sure to consider the environmental aspects, could bring farmers to reduce the impacts of their production process, as suggested also by the new European regulation on GIs. This could constitute a strength for the GI products over the conventional alternatives.

LCA can be helpful to understand which environmental criteria could be added to the specification for increasing the sustainability of the GI production process. In fact, from one side these additions should take into consideration the typical production process, avoiding changing the traditionality traits of the products, but at the same time they should act on the most impactful phases of the specific production (hotspots).

The focus on pears here presented allows the identification of some key factors for environmental sustainability: energy demand and supply, use of fertilizers and pesticides.

For the energy issues, already discussed, some recommendations for

Table 8
Results comparison with literature.

		UoM	This research	[I]	[II]	[III]	[IV]	[V]
Results	GWP100	kg CO_2 eq./FU	0.19	0.29	0.38	0.21[a]	0.32	0.33[a]
	CED	MJ/FU	2.33	–	6.07		–	–
	Water	m^3/FU	0.20	0.21	0.08		–	–
	Yield	t/ha	15.6	18.8	30.0	40[a]	12.5	20.6[a]
System Boundaries	Production of inputs		X	X	X	X	X	X
	Productive years		X	X	X	?	?	?
	Non-productive years			X	X	?	?	?
	Post harvest		X			X	X	X
	Transportation		X	X	X	X	X	X

FU = Functional Unit = kg pears.
[I] (Vatsanidou et al., 2020).
[II] (Tamburini et al., 2015).
[III] (Figueiredo et al., 2013).
[IV] (Audsley et al., 2009).
[V] (Clune et al., 2017).
[a] Average value (an average of different studies was considered).

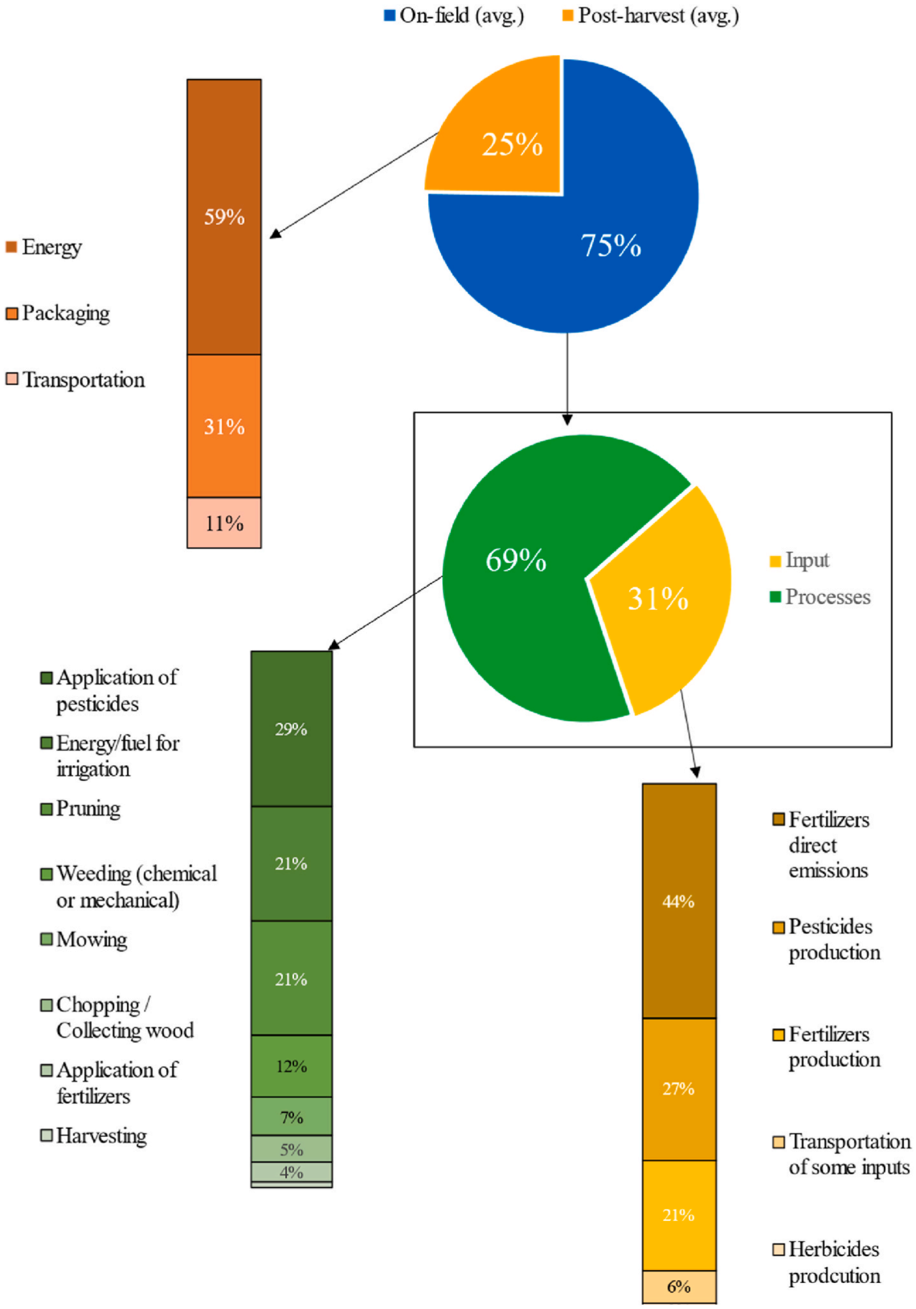


Fig. 16. Mean values for pear supply chain.

improving environmental sustainability can compass the integration of agri-voltaic system, e.g., the development of technical components able to protect against solar radiation or hail and to produce clean energy at the same time, if designed compatibly with economy conditions, agricultural requirements, and landscape impacts. The phase of storage impacts on the energy and matter fluxes. Some varieties of pears can be stored for exceedingly extended periods, adding chemicals that block the maturation process. This is done to guarantee a longer presence on the market and meet the consumers' demand for pears. The promotion of seasonal consumption by policies, market and sensibilization campaigns and offers for customers could help in reducing the storage time and in avoiding the use of chemicals, decreasing the environmental impacts. Further, seasonal consumption may enhance the sensory profile of the product, reinforcing the GI mark. These issues will be the subject of further research developments.

For fertilization, precision agriculture may generate environmental and indirect economic benefits, even if there is the need to investigate their relationship with yield and to aid decision-making about the true sustainability of farming technologies. The topic of pesticides is complex for the pears due to the huge crisis due to the presence of insects and diseases (which presence is in some cases new and mainly due to climate change effects) that cannot be fully controlled by the pesticides allowed by the European regulations, implying a massive use of products (except for organic agriculture). A greater effort in reducing the use of pesticides is needed also for reducing CED and GWP, in addition to other impacts. Therefore, the use of innovative agriculture techniques, if supported by incentives and capacity building, can be effective to that end. A positive compromise can be achieved by prioritizing new agricultural techniques as well as energy efficiency interventions which can allow the maintenance of traditional elements of the process while giving relevant contributions to sustainability as found in our scenarios.

While these improvements may be introduced in the production process of both GI and conventional pears, GI specification offers a unique opportunity for their implementation, due to the presence of the certification and of a producers' organization, which creates connections.

Embedding environmental standards into the GI specification can also have an additional benefit. Both geographical origin and environmentally wise production are credence goods to which certifications may confer credibility toward consumers. Consumers are shown to attribute a greater value to integrated certifications rather than fragmented schemes (Dong and Jiang, 2022). Certain groups of consumers value the local certifications, but they tend to disregard international environmental certifications (Nikolaou and Kazantzidis, 2016). They are more likely to appreciate environmentally friendly production processes only if accompanied by the GI certification. The "greening" of a GI product could also be leveraged to increase its marketability. In addition, the role of GI Consortia, as key stakeholders, should be intensified due to their control over quality and respect for specification rules, involving also third-party companies. Expanding this control system to include somehow environmental sustainability could be evaluated for a better understanding of the main hotspots and related improvement actions.

According to previous considerations, the investment for implementing sustainability policies, strategies and techniques should be compared to the potential reduction of production costs and increasing of the revenues for farmers. As further development, other scenarios should be considered to understand which improvement measures are feasible and appropriate to introduce in the specific GI product, considering the traditionality traits. An analysis of a single non-GI company could also be useful, for a better understanding of the impacts of the introduction of a GI production. Moreover, the elaboration applied should be replicated in other contexts, on different GI products and locations and using different indicators to overcome some of the mentioned limitations of the research. A research network that gathers scholars from different regions and other engageable key stakeholders may sustain such an effort.

The paper results contribute to the current debates on the role of GIs as a channel for sustainable development (Sgroi, 2021), involving different targets, and provides empirical evidence in favor of the idea that GIs may be associated to overall sustainability (economic, social, and also environmental). In fact, the results can support policymakers in the process of making GIs production more sustainable through the new reform (European Commission, 2024). In addition, consortia of producers may benefit from the identification of high-priority environmental improvements to be introduced inside the specification.

Fundings

This study was partially supported by "Research and innovation network on food and nutrition Sustainability, Safety and Security – Working ONFoods" (ONFoods), Project code PE0000003, Concession Decree No.1550 of October 11, 2022 adopted by the Italian Ministry of University and Research CUP D93C22000890001.

Disclosure statement

The authors report there are no competing interests to declare.

CRediT authorship contribution statement

Silvia Falasco: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paola Caputo:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Paola Garrone:** Writing – original draft, Supervision. **Niso Randellini:** Writing – review & editing, Investigation.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142963.

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