

Article

A Life Cycle Assessment and Social Risk Assessment of Organic and Conventional Potatoes in Italy

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Abstract

This study aims to evaluate the environmental and social sustainability of organic and conventional potatoes in Italy using the life cycle thinking approach. Both life cycle assessment and social risk assessment analyses covered agricultural production, industrial processing, and packaging. The results highlight that agriculture and refrigeration are the main environmental hotspots in both systems, with water consumption being the most affected category, and electricity use during the industrial phase being important for several impacts. Organic potatoes received a lower impact for marine ecotoxicity and water consumption but were higher for land use than conventional potatoes, while the two systems were quite similar for human toxicity. The social risk assessment indicated that health and safety, followed by labour rights and decent work, are the most critical areas in the life cycle examined, especially in the Italian agricultural context. Finally, this study suggests that improving energy efficiency, increasing the share of renewable electricity, and strengthening circular flows could enhance sustainability in potato production.

Keywords: life cycle assessment; social risk assessment; organic; conventional; potatoes; sustainability assessment

1. Introduction

Transitioning to sustainable agriculture is essential to achieving European and international sustainability goals, and the methods to do so are currently under discussion [1]. In the coming years, productivity needs to increase to ensure a sufficient food and agricultural product supply, whilst limiting the expansion of agricultural land and enhancing and safeguarding the environment [2]. In this context, it is widely recognised that organic farming has significant potential to mitigate the impacts of traditional agriculture [3]. Indeed, instead of relying on synthetic inputs such as fertilisers and pesticides, organic farming relies on biological processes. In this context, the design of crop rotations and cover crops to sustain soil fertility, the strategic timing of sowing and mechanical cultivation for weed control, as well as the application of biological control methods and natural pesticides for pest management are included [3–5].

Organic production serves a dual social function: it provides a specific market to meet the growing demand for products obtained through natural substances and processes, and



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it provides goods to the public that contribute to animal welfare, environmental protection, and rural development [6].

Moreover, organic farming may typically lead to enhanced performance across various environmental categories, including climate change, biodiversity, water use efficiency, and the quality of soil, water, and air, alongside a variety of ecosystem services [4,5,7–10], whilst using less energy [11].

However, organic farming systems are generally linked to yield decreases of 20–40% for arable crops when compared to conventional systems, greatly depending on local conditions and specific system characteristics [3–5,8,12–14].

As a consequence, organic farming frequently demands larger land areas to achieve the same level of production, as well as its environmental advantages, which may also be less when compared to conventional systems that are managed following the principles of economic and environmental sustainability [3,5,9,15,16].

Therefore, ensuring sustainability in agricultural practice remains a challenge for both farming systems [16]; indeed, being classified as organic does not automatically guarantee that a farm operates sustainably [16,17].

To address this issue, a wide range of methods and tools have been developed to detect and evaluate the impacts generated throughout agricultural processes, with the goal of improving environmental performance [16,18]. Amongst these, life cycle assessment (LCA) is one of the most used, robust, and standardised approaches for assessing the environmental impacts of different agricultural production systems [16,19]. LCA helps assess the inputs, outputs, and potential environmental impacts associated with a product system across its entire life cycle [20]. Its methodological framework [20,21] consists of four interconnected phases: the goal and scope definition, life cycle inventory (LCI) analysis, a life cycle impact assessment (LCIA), and life cycle interpretation.

LCA and the other life cycle-based approaches, such as Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA), are widely considered to be robust tools for supporting more sustainable production and consumption patterns [22–24]. Such methodologies are also ever more recognised as objective frameworks for identifying and assessing the various types of impacts associated with agri-food systems [24–26].

Through such methodologies, the entire supply chain can therefore be taken into account, thus avoiding the so-called “burden shifting”. The comparison of different scenarios related to the products or services under study, as well as the identification of various environmental, economic, and social impacts affecting agri-food chains, is another strength [24–27].

Furthermore, S-LCA is a methodology used to assess the actual and potential social impacts of products and services across their life cycle [28]. Its methodological framework, originally provided by the Guidelines for Social Life Cycle Assessment of Products and Organisations 2020 [28], and recently standardised by ISO 14075:2024 [29], is based on that of an LCA and is therefore structured into the same four phases, but with adaptations.

Finally, regarding the economic dimension, Life Cycle Costing (LCC) is a methodology used to determine the costs associated with a product throughout its entire life cycle [30,31].

Moreover, an eventual integration of LCA, LCC, and S-LCA in a Life Cycle Sustainability Assessment (LCSA) may be used to highlight trade-offs between the three dimensions of sustainability [32–36].

The peculiarities of agri-food products are often considered a challenge in methodological terms; however, LCA has been widely and increasingly applied in the sector [22,24,37]. Moreover, it is widely used for comparing the environmental performance and productivity of conventional and organic farming systems [3,14].

On the other hand, there are few LCC applications—probably due to challenges in adapting it to the involved processes—and there are even fewer S-LCAs [24,26]. This corresponds to the lower consideration of the social dimension of sustainability in the analysed sector, which is still insufficiently accounted for [24,38].

The present study builds upon previous research [39] and aims to assess the environmental impacts and social risks associated with the production activities of a packet of frozen diced potatoes, both in their organic and conventional versions.

Potatoes constitute the fourth most important food crop globally, following rice, wheat, and maize [40]. Given that the global population continues to grow, the demand for staple foods has also been increasing, thus increasing the significance of potatoes, which are considered more advantageous than rice, cereals, and maize [40,41]. Indeed, potatoes, in addition to being an important source of nutrition, form a part of a strategy to provide accessible food and improve livelihoods in rural areas and regions with limited natural resources (especially those limited in water and land). This is also with the consideration of expensive production factors: the versatility of the crop, its ability to grow under different conditions, and its lower GHG emissions compared to other crops make potatoes a favourable choice, as well as a climate-friendly crop [42].

Potatoes can be used in a variety of ways, with approximately half being consumed in their fresh form, and the other half being processed into food ingredients, starch, or animal feed [40,43]. In addition, the demand for processed products (e.g., frozen potatoes, French fries, crisps) has been increasing as well [40]. At the same time, industrial processing of potato-derived products is considered to be responsible for large amounts of waste (e.g., peels, mash, pulp, process water, etc.), without a market value [40]. This is despite the fact that potatoes, which are rich in carbohydrates, proteins, and bioactive compounds, may be used and converted into byproducts, thus enabling circular economy-related practices [40].

A comprehensive literature review was performed to highlight the research gap that this article will try to fill, with a particular focus on comparative LCA studies, examining conventional and organic potato production systems (Section 2). Furthermore, the rest of the article is structured as follows: in Section 3, the materials and methods used in this study are described; Section 4 includes the results of the case studies, as well as their discussion; and in Section 5, some conclusions are drawn, and future developments are reported.

2. Literature Background

Although several LCA studies have been conducted on potato cultivation, only a limited number provide a direct comparison between organic and conventional production systems.

To reconstruct the current state of knowledge on the topic, a systematic literature review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram [44] for study identification, screening, and inclusion (Figure 1).

The search strategy was based on the query string “(“life cycle assessment” OR LCA) AND (potato*)”, which was applied to the Scopus and Web of Science Core Collection databases. Initially, no restrictions were imposed, yielding 420 records (219 from Scopus and 201 from Web of Science). Subsequently, the search results were refined by restricting document types to articles and reviews in English at any publication stage, also including “in-press” (in Scopus) and “early access” publications (in Web of Science). Following this filtering step, the number of records was reduced to 182 and 192 in Scopus and Web of Science, respectively. After merging the results from both databases (374) and removing duplicate records (139), a total of 235 unique publications remained for the screening phase.

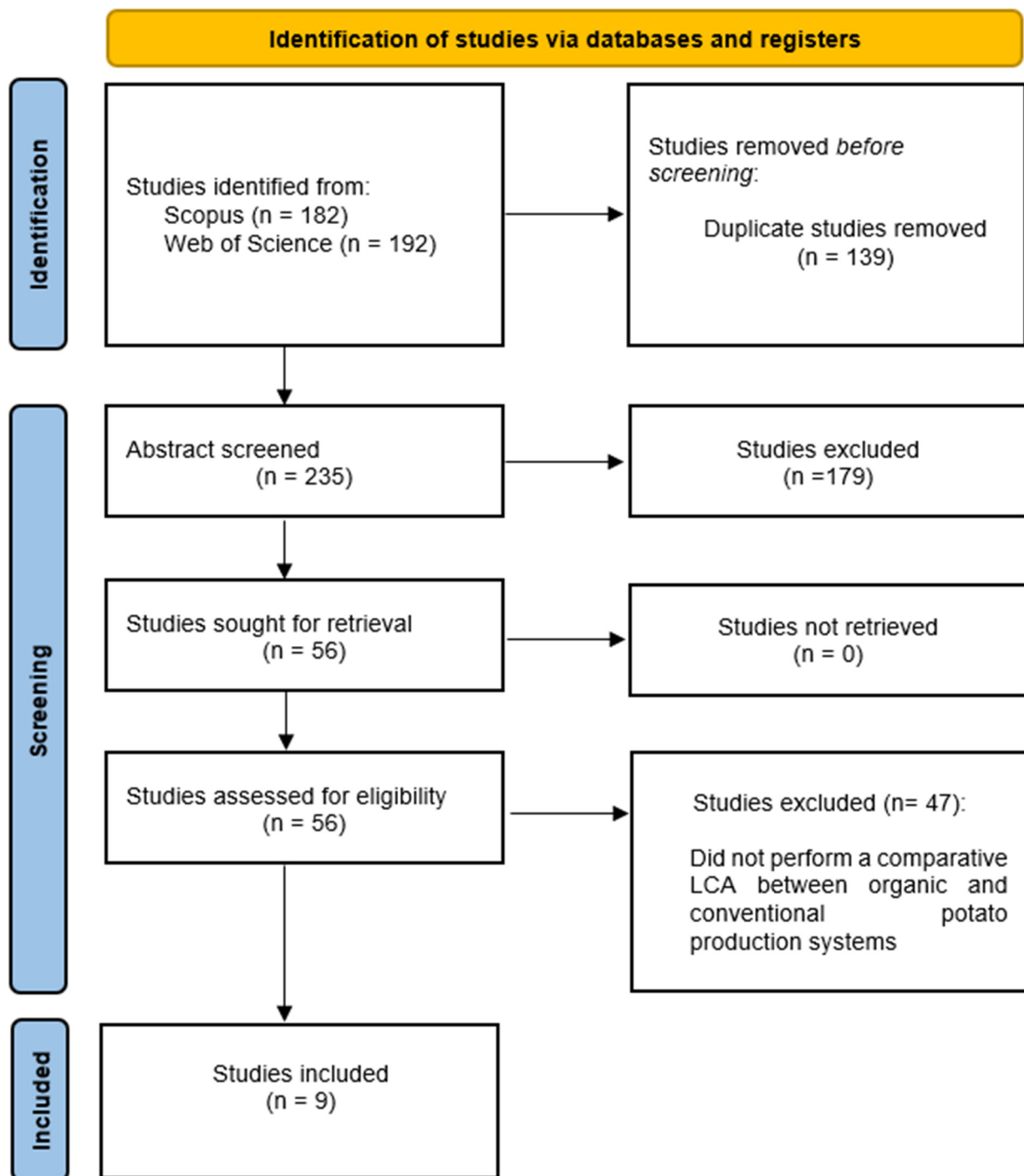


Figure 1. PRISMA 2020 flow diagram for the systematic review of this article (adapted from [44]).

The title and abstract screening process was carried out to identify studies specifically addressing the application of LCA to potato production systems. Studies were excluded if they did not employ LCA methodology or if they focused on circular economy applications derived from potatoes rather than on potato production itself. Examples of excluded studies included those investigating bioethanol production from potato waste biomass or the development of food-packaging materials based on potato starch. Furthermore, studies containing only generic references to food crops, or focusing on crop-rotation systems, or dietary patterns were excluded.

A subsequent full-text assessment was performed to evaluate the eligibility of the remaining studies (56). Consistent with the objectives of the present review, only studies

(9) conducting comparative LCAs of organic and conventional potato production systems were ultimately included in the final dataset (Table 1).

Table 1. Results of the systematic literature review.

	Year	Author	Title	Publication Title
[45]	2010	Williams, A.G.; Audsley, E.; Sandars, D.L.	Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling	International Journal of Life Cycle Assessment
[46]	2012	Refsgaard, K.; Bergsdal, H.; Berglann, H.; Pettersen, J.	Greenhouse gas emissions from life cycle assessment of Norwegian food production systems	Acta Agriculturae Scandinavica A: Animal Sciences
[47]	2023	Kumar, R.; Bhardwaj, A.; Singh, L.P.; Singh, G.	Quantifying ecological impacts: A comparative life cycle assessment of conventional and organic potato cultivation	Ecological Modelling
[48]	2013	Moudrý, J.; Jelínková, Z.; Jarešová, M.; Plch, R.; Moudrý, J.; Konvalina, P.	Assessing greenhouse gas emissions from potato production and processing in the Czech Republic	Outlook on Agriculture
[49]	2013	Moudrý Jr., J.; Jelínková, Z.; Moudrý, J.; Jaroslav, B.; Marek, K.; Petr, K.	Influence of farming systems on production of greenhouse gas emissions within cultivation of selected crops	Journal of Food, Agriculture and Environment
[5]	2019	Boone, L.; Roldán-Ruiz, I.; Van linden, V.; Muylle, H.; Dewulf, J.	Environmental sustainability of conventional and organic farming: Accounting for ecosystem services in life cycle assessment	Science of the Total Environment
[50]	2021	Scuderi, A.; Cammarata, M.; La Via, G.; Pecorino, B.; Timpanaro, G.	Life-cycle assessment of biofortified productions: The case of selenium potato	Applied System Innovation
[16]	2021	Timpanaro, G.; Branca, F.; Cammarata, M.; Falcone, G.; Scuderi, A.	Life cycle assessment to highlight the environmental burdens of early potato production	Agronomy
[51]	2025	Holka, M.; Kowalska, J.	Comparative analysis of environmental impacts of wheat and potato production in conventional and organic systems	Journal of Plant Protection Research

Williams et al. [45] assessed the environmental performance of potatoes (amongst other agricultural products) in England and Wales, comparing both organic and conventional production systems. In particular, they concluded that although pesticide use is lower in organic production, other burdens are slightly higher (though not significantly). The reduced use of fertilisers in organic systems is compensated by the higher energy demand associated with field operations and labour requirements (13% more energy than conventional production), as well as lower yields in the case of organic potatoes [45]. Refsgaard et al. [46] compared organic and conventional farming systems across various food production systems in Norway, including potato production. Focusing on greenhouse gas (GHG) emissions and land use, the study demonstrates that conventional farming systems generally produce higher GHG emissions than organic systems, although they typically require less land [46]. Moudrý et al. [48] focused on GHG emissions associated with selected potato farming systems, both organic and conventional, in Czechia. The study

found that the lower emissions associated with organic farming were offset by the higher emissions related to the transport of organic products [48]. In a different study, Moudrý et al. [49] presented a simplified LCA of several crop productions, including potatoes under both conventional and organic systems in Czechia. Their analysis showed a reduction in emissions associated with organic production for potato cultivation [49]. Boone et al. [5] compared the environmental impacts of potatoes and other selected agri-food products under both conventional and organic farming systems. The results showed that for approximately half of the food products analysed, including potatoes, organic farming provides environmental benefits, with lower resource consumption than conventional cultivation methods [5].

On the other hand, Scuderi et al. [50] examined the cultivation of selenium-enriched potatoes and compared them with conventionally grown ones, highlighting that the fortified product was more sustainable than the conventional counterpart. Timpanaro et al. [16] conducted a comparative LCA of organic and conventional potato production in Sicily. Their results indicated that the organic system is more sustainable when impacts are expressed per hectare of cultivated land, whereas, when assessed per kilogram of product, organic production shows higher environmental impacts. The study also highlighted that organic farming often requires additional interventions to improve yields and achieve better performance [16].

The study by Holka and Kowalska [51] focused on the production of winter wheat and potatoes, comparing conventional and organic farming systems, highlighting that organic farming generally has lower environmental impacts, although in both systems, the use of fertilisers remains the main environmental hotspot.

Although all studies confirm a trend towards improved environmental performance in organic farming, LCA studies highlighted considerable variability in resource efficiency [3,16] for the outputs of the production methods. This is partly due to the fact that the environmental performance of organic farming improves when the agricultural system is managed in a more integrated, holistic manner [16,52].

Moreover, all studies primarily focus on the agricultural phase, adopting system boundaries from cradle to farm gate and therefore excluding post-harvest stages. However, this phase should not be overlooked, as post-harvest activities—such as transport, processing, storage, packaging, and refrigeration—make a significant contribution to the overall environmental impacts [40,53,54].

Finally, amongst the studies mentioned, only one [18] considered the economic dimension of sustainability, while none of them addressed the social one.

More so, in general, regarding the social aspects, based on a review of the literature on the topic [24] and its recent update [55], no S-LCA case studies on potatoes have been conducted.

This study may therefore be the only LCA study conducted on this product that goes beyond the agricultural phase to include the industrial phase, covering both conventional and organic production while also incorporating a comprehensive mapping of the associated social risks.

Against this background and gap, the present study aims to assess the environmental performance of conventional and organic potato production across the agricultural and industrial phases and identify the associated social risks. These objectives are pursued to address the following research questions:

1. What are the main environmental life cycle hotspots of the organic and conventional potatoes under study, considering both the agricultural and industrial phases?
2. What are the most influenced environmental impact categories for these two systems under study?

3. What are the main social risks associated with potato production across both the agricultural and industrial phases?

3. Materials and Methods

3.1. LCA Case Study

3.1.1. Goal and Scope Definition

Both the agricultural company and industrial facilities are located in the Piana del Fucino, in the region of Abruzzo in Italy. Such an area represents the highest productivity index (approximately 55,000 kg/ha) and the largest producer of common potatoes in the country. The potato variety considered is “Agata”, cultivated at an altitude of 670 m in clay-loam soil in 2022, a particularly dry year, with a yield of 40,000 kg/ha for organic farming and 53,000 kg/ha for conventional farming. The system boundary analysed in the study included the agricultural and industrial phases, also comprising the packaging of the finished product. As illustrated in Figures 2 and 3, the two product types, while very similar, differ in certain aspects. Organic farming (Figure 2) includes harrowing and shredding of leaves and shrubs, which are not carried out in conventional farming (Figure 3). However, conventional farming includes chemical fertilisation, which is not required in organic farming. Regarding the industrial phase, both product types undergo similar processing steps, as they are handled by the same production line. The difference lies in that the washing and disinfection stages exclusively include chlorinated water for the organic product. In general, the functional unit choice (FU) in terms of “per area” or “per mass” may influence the assessments in the agri-food sector: per area assessments tend to attribute higher impacts to conventional systems, whilst some indicators demonstrate higher values for organic systems when the data are related to production yield [56]. For this article, a mass-related FU was considered for both studies (450 g of frozen product), in accordance with Notarnicola et al. [22]. Moreover, it is to be highlighted that given the specific characteristics of the two systems under analysis, the results cannot be generalised to all potato production systems.

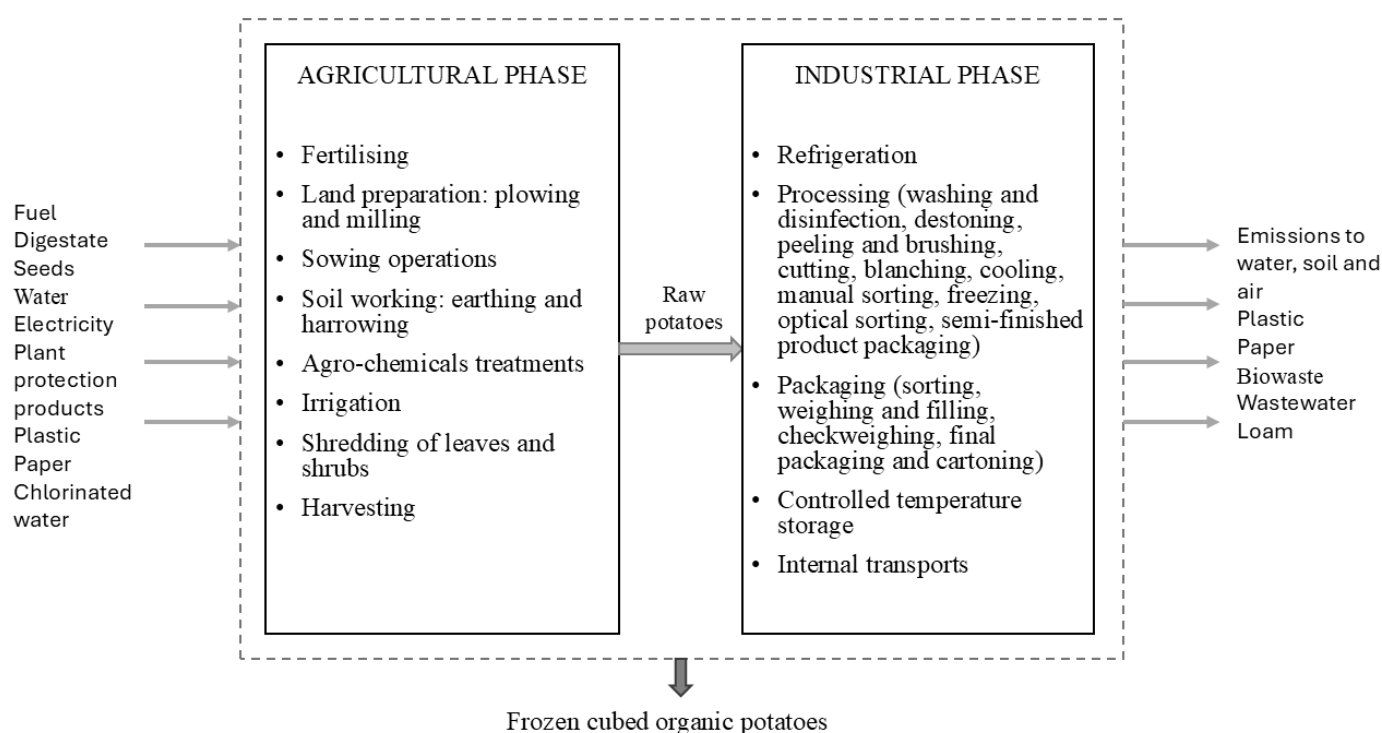


Figure 2. System boundary of the organic product (Source: elaborated by the authors).

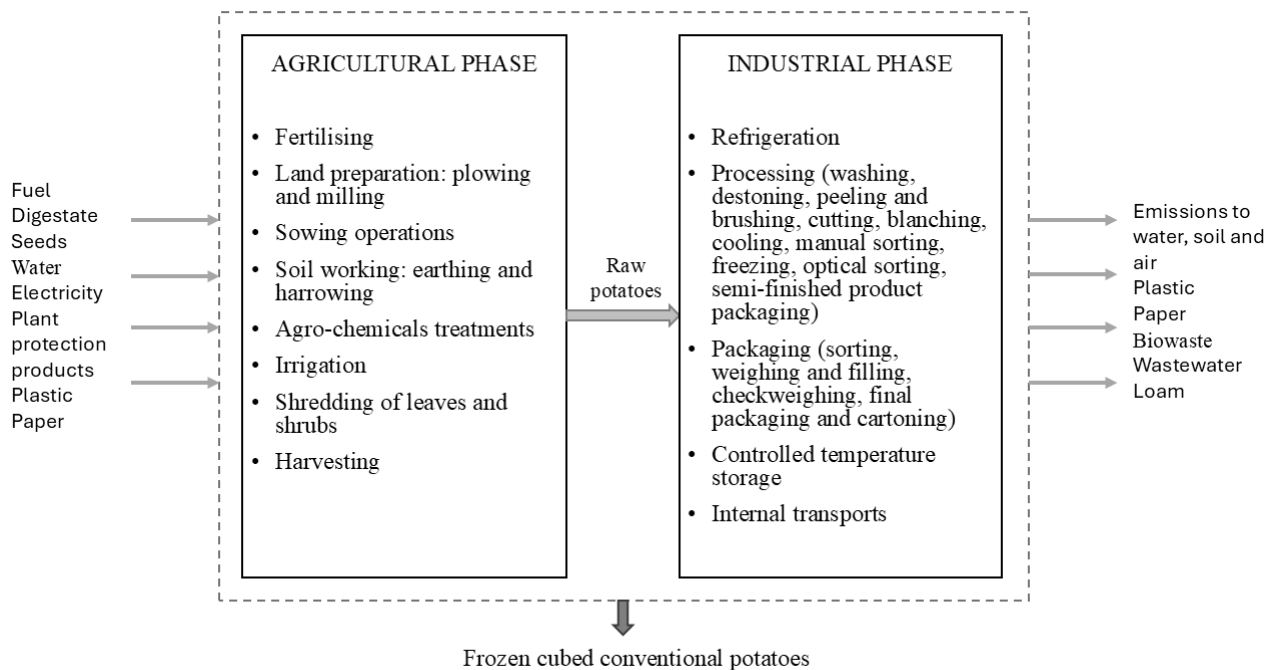


Figure 3. System boundary of the conventional product (Source: elaborated by the authors).

3.1.2. Life Cycle Inventory (LCI)

Agricultural Phase

For the agricultural phase, the farm provided the necessary information by completing ad hoc data collection sheets. The entire field is cultivated for 5 ha under organic management and 5 ha under conventional management. Data collection was carried out for the purchase of plant protection products, transport of irrigation equipment, seed, and fertilisers from storage to the field. Moreover, data for plant protection products, water consumption for treatments and irrigation, seeds, liquid digestate, and transporting raw potatoes to the factory were collected.

Irrigation

The irrigation system considered involves the use of a pressurised irrigation network, which, through a metre at the water pumping station located near the field, allows for the precise measurement of the water actually used (2043 m³/ha in organic farming and 3580 m³/ha in conventional farming, as shown in Table 2) and the energy consumed for pumping.

The total energy consumed in a calendar year was taken into consideration from the Avezzano-Celano basin pumping station manager alongside the water consumption recorded by the metering system and effectively used for irrigation. As reported in Table 2, in the case of conventional production, initial irrigation was carried out by pumping water via a tractor, which also consumed diesel fuel, and as such, was accounted for.

Table 2. Irrigation-related water and energy consumption (Source: firm under study).

ORGANIC FARMING			
Date	h	m ³	kWh
22 July 2022	6	830	489.7
30 June 2022	10	533	314.47
16 June 2022	14	680	401.2
Total organic	20	2043	1205.37

Table 2. *Cont.*

CONVENTIONAL			
Date	h	m ³	kWh
18 July 2022	14	780	460.2
8 July 2022	24	860	507.4
29 June 2022	14	730	430.7
14 June 2022	14	710	418.9
1 June 2022 (pumping via tractor)	6	500	48
Total conventional	73	3580	1865.2

Phytosanitary Products

When modelling in software, since some products were of natural origin and unavailable in the software databases, their sole packaging was taken into account. The weight of phytosanitary product packaging was also directly measured. Regarding the final destination of the packaging, its transport to the waste collection centre and recycling were considered. This is a limitation of the study, which can, however, be regarded as marginal due to the fact that the non-considered products are of natural origin. It should be furthermore noted that, in this study, for copper-based fungicides, the use of 100% regenerated copper of national origin, as declared by the firm, was not considered, as it was unavailable in the database; instead, a generic copper was selected.

This study takes into account the transport of phytosanitary products to the facilities under study, as well as the disposal of their packaging. The average distance to and from suppliers was calculated to be 8.8 km (round trip), given that the suppliers vary, and each purchase includes substances used across multiple hectares. The transport mode used for the disposal of packaging at the waste collection centre was assigned to each phytosanitary product.

The fertiliser used in conventional cultivation is a simple mineral fertiliser composed of mixed phosphate salts (CaO-MgO-SO₃) with trace elements 16(8-2-22). The active ingredients included (and considered in this study) are as follows: magnesium oxide (MgO 2%), sulphur trioxide (SO₃ 22%), and phosphorus pentoxide (P₂O₅ 16%). The various emissions were calculated following Zampori and Pant [57].

Seed

The seed used (2200 kg/ha), purchased from a company based in the Campania region, originated from the northern part of the Netherlands. The distance between Emmeloord (the place of origin) and Celano (1750 km) was therefore considered, assuming transport by articulated lorry.

Liquid Digestate

The liquid digestate used for fertilisation (66,000 kg/ha) originated from a local biogas plant located 3.5 km from the field and 1 km from the processing facility considered in the study. The latter, in turn, supplied the plant with organic residues from processing activities, thus closing the production cycle. For data entry in the software, organic residues from processing and compost were used, based on analytical data provided by the firm itself, which reported the exact percentages of dry matter, phosphorus, and nitrogen actually contained within the digestate. For these entries, allocation by mass was performed for the cases where the residues (e.g., from peeling and brushing, manual and optical sorting, and freezing) from the industrial phase were taken as inputs within the agricultural one.

Industrial Phase

Data collection for the agro-industrial phase was carried out by considering a processing capacity of 5 t per hour. Out of this amount, 0.2 t consisted of soil waste that was disposed of at an authorised facility located 20 km away, 0.3 t was lost during blanching (a process that naturally reduces the weight of the potatoes), and 1.5 t constituted the total organic residue destined for the biogas plant located 1 km from the processing facility. At the end of processing, approximately 3 t of frozen processed product remained, packed into 6666 bags of 450 g each using 10 g per bag of plastic film. These were subsequently boxed in recycled cardboard (containing 12 individual packs) with a weight of 30 g per box. For the packaging purchase, both outbound and return transport distances were considered. For the LDPE film and the cardboard, specific related entries were taken from the Ecoinvent database (corrugated board box, recycled (RER) and packaging film, LDPE (RER)).

At the beginning of organic product processing, the production line must first be washed and disinfected using 2 m³ of water and chlorine (14%), which refers to 100 t processed. Such a parameter is not required for the conventional production system.

Energy Consumption

The allocation of energy consumption for the refrigerated cells was calculated based on the nominal power of the cell, the storage duration, and the percentage attributable to 5 tonnes, resulting in an assigned consumption of 1440 kWh. The same principle was applied to the temperature-controlled cells operating at −21 °C, considering the nominal power of the cell and a storage period of 10 days (between the processing line and the packaging line, as well as for final storage).

With regard to internal transport, the use of an electric forklift was considered.

Wastewater

The wastewater generated throughout the entire processing cycle was treated in the internal purification plant of the agri-food facility and subsequently reintroduced into the irrigation channels of the fields, thus rendering the cycle substantially closed.

All in all, the LCI data reported in the study were included in the SimaPro software [58], using databases such as Ecoinvent, ELCD, Agri-footprint, and Agribalyse. Amongst the available datasets, those most representative of the analysed context were selected.

3.1.3. Life Cycle Impact Assessment (LCIA)

In order for the impacts to be assessed, the ReCiPe 2016 Midpoint (H) [59] method was used, given that it provides a comprehensive set of impact categories and has been applied in LCA studies of the sector (e.g., [37,60]).

3.2. Social Risk Assessment

The social risk assessment conducted allows for identifying the social hotspots, i.e., locations and/or activities in the life cycle of the analysed product where social risks occur [28]. A social risk describes the probability of a social problem taking place [28], and it is important for understanding the analysed context at the national and sector levels in order to support the decision-making process. The mapping of social risks and hotspots associated with potato production was carried out using the Risk Mapping Tool, a Social Hotspots Database (SHDB) web-based tool [61].

SHDB is “an extended input/output Life Cycle Inventory database providing a solution to enable (1) the modelling of product systems and (2) the initial assessment of potential social impacts” [62]. The SHDB is built upon the Global Trade Analysis Project

(GTAP) general equilibrium model, which covers economic sectors across countries and regions, and employs monetary linkages between processes [61].

Furthermore, the SHDB offers data on social indicators organised into social impact subcategories, impact categories (i.e., “Labor Rights and Decent Work”, “Health and Safety”, “Governance”, “Society” and “Community”), and stakeholder groups (i.e., “Workers”, “Local Communities”, “Value Chain Actors”, and “Society”) [61].

Each indicator is assigned a risk level (“low”, “medium”, “high”, “very high”) based on its underlying data, according to the threshold specified in the database documentation [61]. The SHDB employs worker hours as its activity variable and calculates the social risks associated with the product under analysis through a specific impact assessment method [61].

The same components of SHDB (i.e., information on social risks at a country-sector level, information on labour intensity across economic sectors, and information on supply chain composition and geographic location by country-specific sectors) underpin the Risk Mapping Tool [61].

The Risk Mapping Tool enables users to immediately and intuitively identify the social risks associated with specific production activities at both the sectoral and country levels, although it does not allow for a comprehensive visualisation of the entire supply chain [61].

In particular, several approaches can be adopted to map social risks. The analysis may focus on a single indicator, examine multiple indicators within a subcategory and an impact category, or consider the overall risk [61].

In this way, the Risk Mapping Tool enables the visualisation of sector-specific risks at a global scale through an interactive map, supports the analysis of multiple social issues, and allows for the comparison of social risks across country-specific sectors, facilitating the identification of contributing issues among the impact categories [63]. The Risk Mapping Tool enables enterprises to identify social risks across their own sites and supply chains, supporting them in directing efforts where they are most needed to mitigate risks [64].

To carry out the analysis of the social risks associated with potato production in Italy, it was first necessary to identify the relevant economic sector in the Risk Mapping Tool by applying the appropriate sectoral correspondence GTAP table [61].

Once the relevant sector had been determined, the analysis could proceed accordingly.

4. Results and Discussion

4.1. LCA Case Study

4.1.1. Agricultural and Industrial Phase of the Organic Potatoes

At the characterisation results of the finished product (Figure 4) level, while considering the agricultural phase and that of processing and packaging, the processes that have the greatest impact on the functional unit can be observed. The agricultural phase has the greatest impact, particularly for marine eutrophication (for which it is almost entirely responsible), stratospheric ozone depletion (95.3%), land use (91.3%), human toxicity (non-carcinogenic) (80.7%), and mineral resource scarcity (71.4%). Refrigeration also made a significant contribution, in which raw potatoes are stored prior to being introduced to the processing line. For this input, electricity, required for its operation, and thus its impacts can be attributed to the energy consumption and, consequently, to the employed energy mix. Refrigeration contributes substantially to the impact categories of water consumption (59.7%), human toxicity (carcinogenic) (58.2%), terrestrial ecosystem ozone formation (46.7%), and fine particulate matter formation (46%). The phase that appears as “positive” in the Figure corresponds to the blanching and cooling process. This result can be attributed to the reduction in product weight that is naturally caused by this process.

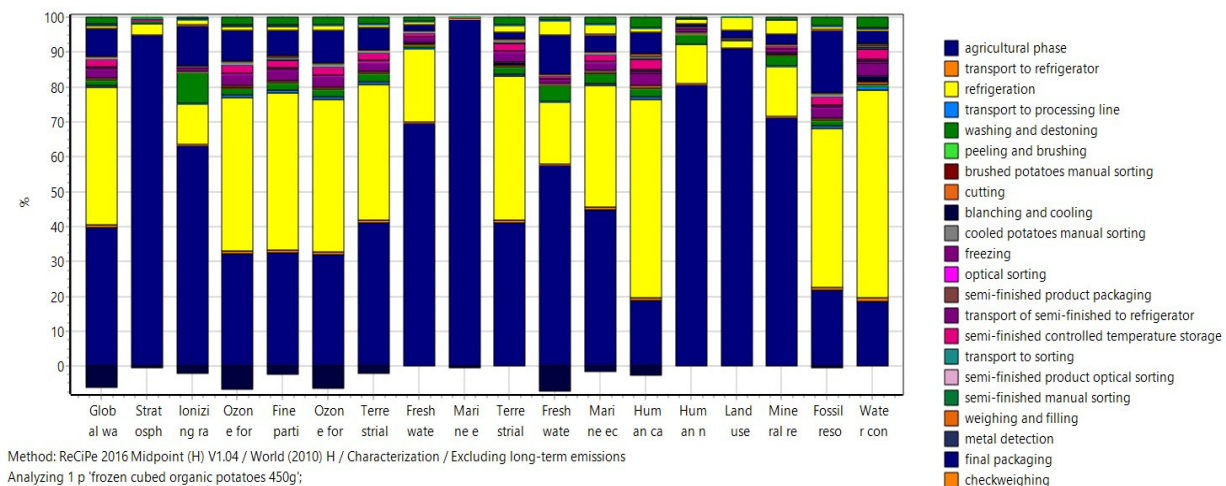


Figure 4. Characterisation results for the organic potatoes. Source: [58].

In Figure 5, the normalisation results of the finished product are shown; it is evident that the most significantly influenced environmental impact category is water consumption. To a lesser extent, though still relevant, are the impacts associated with the categories of human toxicity (carcinogenic) and terrestrial ecotoxicity.

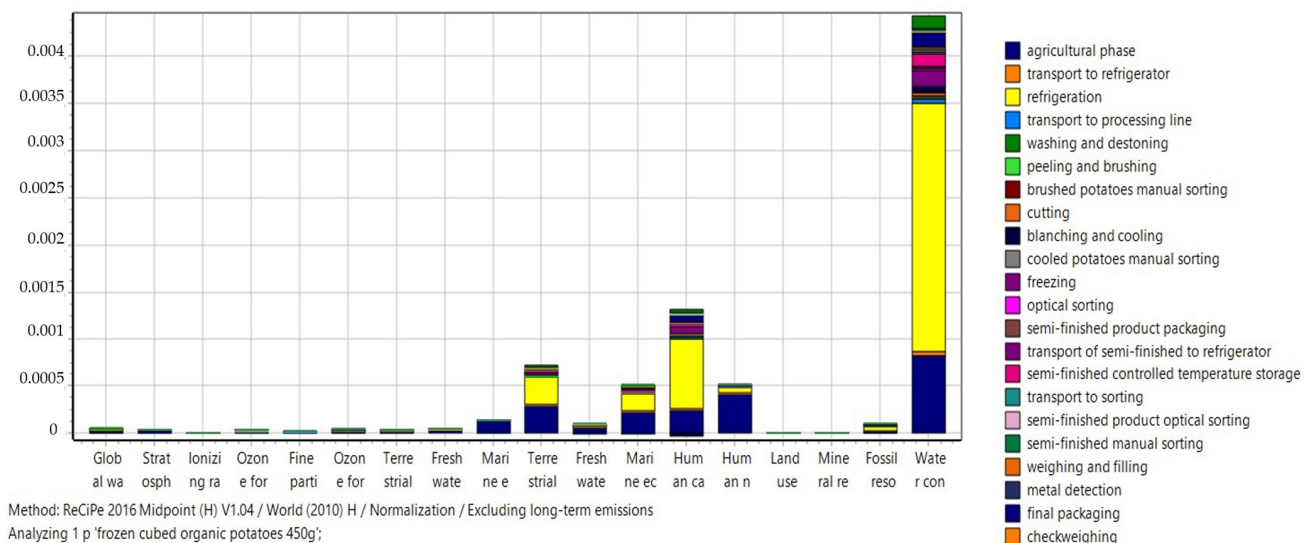


Figure 5. Normalisation results of the organic potatoes. Source: [58].

Of the total for the water consumption category (1.18 m^3), 78.73% is attributable to low-voltage electricity, an input assigned to the industrial processing, and therefore dependent on the energy consumption and the mix adopted by the company (Table 3). Indeed, the LCIA method used attributes to the adopted Italian energy mix a significant percentage of water consumption-related impact. Of the 0.929 m^3 of low-voltage electricity-related impact, 75.9% is related to refrigeration, 4.7% to the freezing tunnel, 4% to the storage of the semi-finished product, and 3.8% to the final storage of the finished product. Tap water (0.105 m^3) accounts for 8.9% of the total water consumption, while the portion attributable to the agricultural phase amounts to 0.102 m^3 . Medium-voltage electricity represents 7.39% of the water consumption category; since the water pumping system uses it for irrigation,

its impact depends on the energy mix employed by the irrigation authorities. As shown in Table 3, the LPDE packaging of the finished product (2.55%) and the compost derived from liquid digestate (1.64%, excluding the fraction of organic waste originating from in-factory processing) also contribute to a lesser extent.

Table 3. Characterisation results for the organic potatoes: First 5 results for “Water consumption”. Source: [58].

Processes	Total (m ³)
Total of all processes	1.18
Electricity (industry)	0.929
Tap water	0.105
Electricity (agriculture)	0.0872
LDPE packaging film	0.0301
Compost	0.0194

The normalisation results (Figure 4) demonstrate that the second most affected impact category for the finished product is human toxicity (carcinogenic), with a total of 0.00356 kg 1,4-DCB. The greatest contribution, of 76.97%, is attributable to energy use during industrial processing (0.00274 kg 1,4-DCB), almost entirely due to refrigeration (75.5%) due to the specific Italian energy mix obtained from the Ecoinvent database and the LCIA method characterisation factor attributions. Water use accounts for 6.88% of the total, almost entirely attributable to the agricultural phase (97.1%). As reported in Table 4, the plastic packaging of the finished product contributes 5.31% of the impact, the organic seed 4.16%, and the compost 3.01%.

Table 4. Characterisation results for the organic potatoes: First 5 results for “Human toxicity (carcinogenic)”. Source: [58].

Processes	Total (kg 1,4-DCB)
Total of all processes	0.00356
Electricity (industry)	0.00274
Tap water	0.000245
LDPE packaging film	0.000189
Organic seed	0.000148
Compost	0.000107

The third most significant impact category is terrestrial ecotoxicity (Table 5). Of the total 0.735 kg 1,4-DCB resulting from the sum of all processes, 54.56% is due to low-voltage electricity consumption in industrial processing, of which 41.4% is attributable to refrigeration, 25% to the freezing tunnel, 20.6% to the storage of the semi-finished product, and 20% to the final storage. During modelling, the proxy of “Copper oxide” was used due to the fact that the database did not contain the option for 100% regenerated copper of national origin, which is actually present in the fungicide. Given that this accounted for 16.33% of the impact, the real value could therefore be somewhat lower. The organic seed contributes 16.05% of the impact due to its production and refrigeration, and 2.23% due to its transport within Italy. Tap water accounts for 2.35% of the impact of this category.

Table 5. Characterisation results for the organic potatoes: First 5 results for “Terrestrial ecotoxicity”. Source: [58].

Processes	Total (kg 1,4-DCB)
Total of all processes	0.735
Electricity (industry)	0.401
Copper oxide	0.12
Organic seed	0.118
Tap water	0.0173
Transport	0.0164

4.1.2. Agricultural and Industrial Phases of Conventional Potatoes

Figure 6 shows the characterisation results for conventional potatoes: the dominant phase is agriculture, followed by the initial refrigeration of the product.

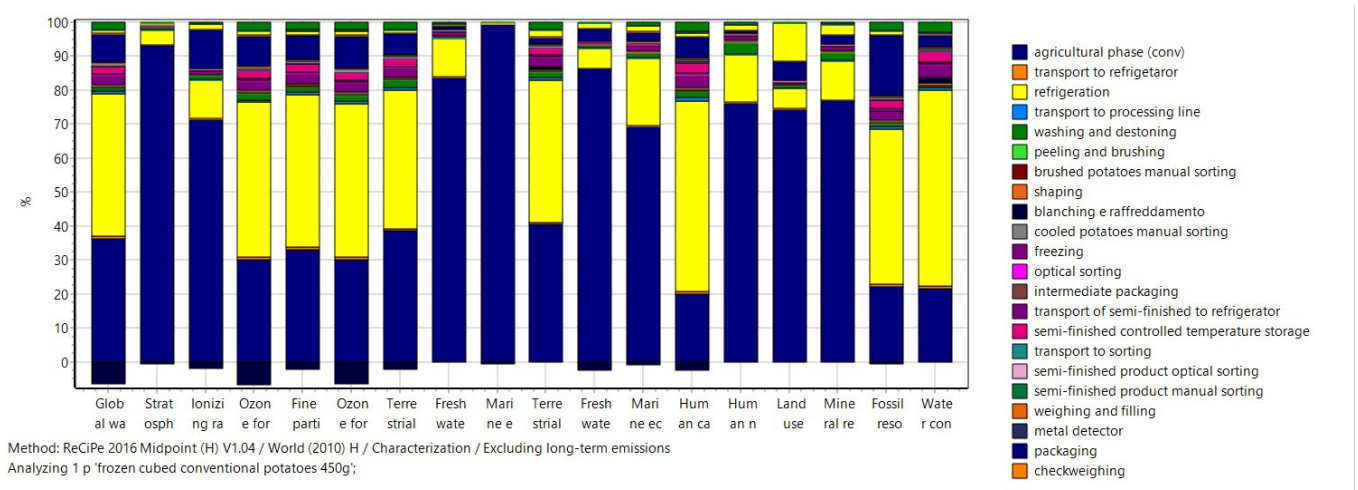


Figure 6. Characterisation results for conventional potatoes. Source: [58].

Indeed, the agricultural phase alone is responsible for nearly all of the marine eutrophication impact (approx. 100%), stratospheric ozone depletion (93.9%), freshwater ecotoxicity (88.4%), and freshwater eutrophication (83.7%), as well as a substantial share of mineral resource scarcity (76.9%), non-carcinogenic human toxicity (76.3%), land use (74.5%), ionising radiation (73%), and marine ecotoxicity (69.9%).

The second most significant phase is refrigeration, which takes place prior to industrial processing. This phase has an important impact on carcinogenic human toxicity (57.5%), water consumption (57.6%), and fossil resource scarcity (46.1%), as well as a considerable contribution to global warming (44.8%) and ozone formation (48.8% for human health and 48.4% for terrestrial ecosystems). As for the organic system, the phase shown below zero in the Figure is blanching, which is caused by the natural loss of product weight.

The analysis of the normalised results (Figure 7) indicates that water consumption is the most influenced category. As reported in Table 6, the total water consumption required to produce a 450 g package amounts to 1.22 m³. Out of this, 76.15% is attributable to electricity consumption in the industrial processing, including 0.705 m³ for refrigeration, 0.044 m³ for the freezing tunnel, 0.0376 m³ for the storage of the frozen semi-finished product, and 0.0352 m³ for final storage.

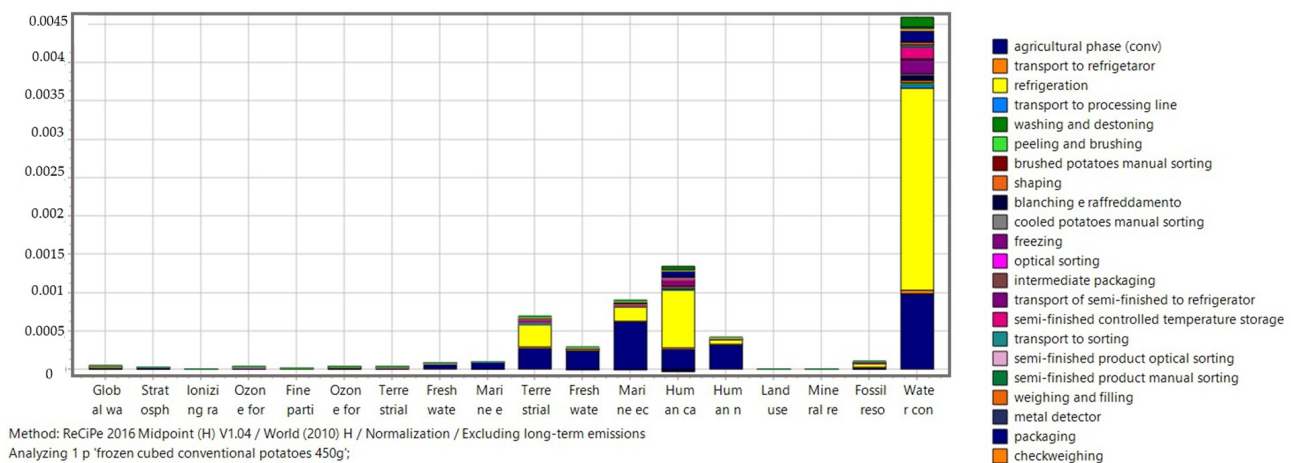


Figure 7. Normalisation results for conventional potatoes. Source: [58].

Table 6. Characterisation results for conventional potatoes: First 5 results for “Water consumption”. Source: [58].

Water Consumption	
Processes	Total (m ³)
Total of all processes	1.22
Electricity (industry)	0.929
Tap water	0.137
Electricity (agriculture)	0.0992
Film LDPE (packaging)	0.0302
Compost	0.0146

Regarding direct water use (0.137 m³), 0.135 m³ is associated with the agricultural phase, whilst 0.0992 m³ is related to water pumping within the facility. Additionally, 2.48% of the total impact in this category is attributable to plastic packaging, and 1.2% to compost, a component of the liquid digestate.

The second most influenced impact category is human carcinogenic toxicity (0.00361 kg 1,4-DCB). Out of the total impact (Table 7), 75.9% is attributable to electricity used in the industrial phase, including 0.00207 kg 1,4-DCB for initial refrigeration, 0.00013 kg 1,4-DCB for the freezing tunnel, 0.000111 kg 1,4-DCB for semi-finished product storage, and 0.000104 kg 1,4-DCB for final storage. Additionally, 5.26% of the total impact in this category is attributable to packaging materials (mainly the use of LDPE film).

The third most influenced impact category is marine ecotoxicity (0.000922 kg 1,4-DCB). Out of the total impact, 51.63% is attributable to seed production and refrigeration, while 26.25% is associated with the electricity used in processing, including 0.000184 kg 1,4-DCB for initial refrigeration. The remaining inputs reported in Table 8 are attributable to the agricultural phase, as they are contained in fertilisers and fungicides (e.g., phosphate fertiliser, copper oxide, magnesium oxide).

Table 7. Characterisation results for conventional potatoes: First 5 results for “Human carcinogenic toxicity”. Source: [58].

Human Carcinogenic Toxicity	
Processes	Total (kg 1,4-DCB)
Total of all processes	0.00361
Electricity (industry)	0.00274
Tap water	0.000322
Film LDPE (packaging)	0.00019
Conventional seed	9.77×10^{-5}
Compost	8.1×10^{-5}

Table 8. Characterisation results for the conventional potatoes: First 5 results for “Marine ecotoxicity”. Source: [58].

Marine Ecotoxicity	
Processes	Total (kg 1,4-DCB)
Total of all processes	0.000922
Conventional seed	0.000476
Electricity (industry)	0.000242
Phosphate fertiliser	3.48×10^{-5}
Copper oxide	2.73×10^{-5}
Magnesium oxide	2.35×10^{-5}

4.1.3. Sensitivity Analysis

In order for the robustness of the results to be assessed, a sensitivity analysis was performed. Given that the reference year under analysis was quite dry, a sensitivity analysis was performed for the amount of water consumption by taking into account the reduced rainfall by 45% for 2022 [65], the average water amount of 600 mm required for potatoes [66], as well as the average additional irrigated water required in case of reduced rainfall [67]. The first new scenario (i.e., “scen no dry”) for both systems was therefore set for a reasonable reduction of 20% in irrigation water.

Regarding organic potatoes, the first new scenario received lower impact scores, but it does not present a significant decrease (please refer to Figure 8), thus confirming the results in terms of the impact categories’ ranking. Indeed, regarding the three most influenced environmental impact categories, water consumption experienced a 1.73% decrease, human carcinogenic toxicity 1.35%, and finally, 0.46% for terrestrial ecotoxicity.

As far as the conventional system is concerned, the sensitivity analysis confirms the base scenario results in terms of the impact categories ranking, as well. Furthermore, in this case, the reduction in the impact is also not important (Figure 9). Indeed, regarding the three most influenced environmental impact categories for the conventional potatoes, water consumption saw a 2.19% decrease, human carcinogenic toxicity 1.75%, and finally, 0.42% for marine ecotoxicity.

Regarding the second new scenario, this was set for the energy mix used for the industrial phase, given the importance of energy consumption in this phase. Therefore, in the new scenario (“scen_renew”), the energy mix was modified as follows: 50% from the original Italian electricity grid and 50% from renewable resources.

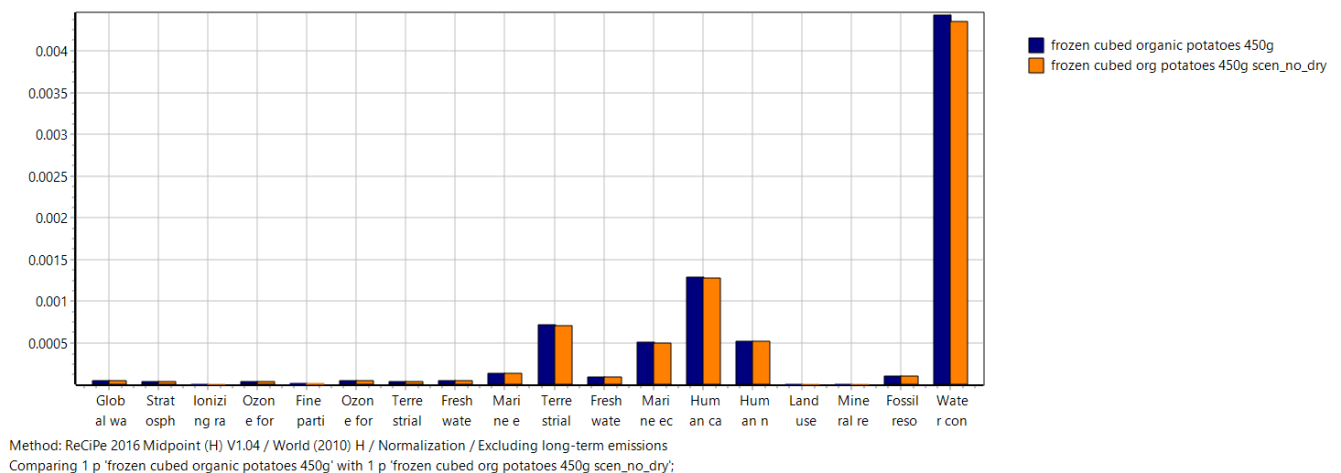


Figure 8. Normalisation results for organic potatoes scenario comparison between the base scenario and the scenario of lower required irrigation quantities (“scen_no_dry”). Source: [58].

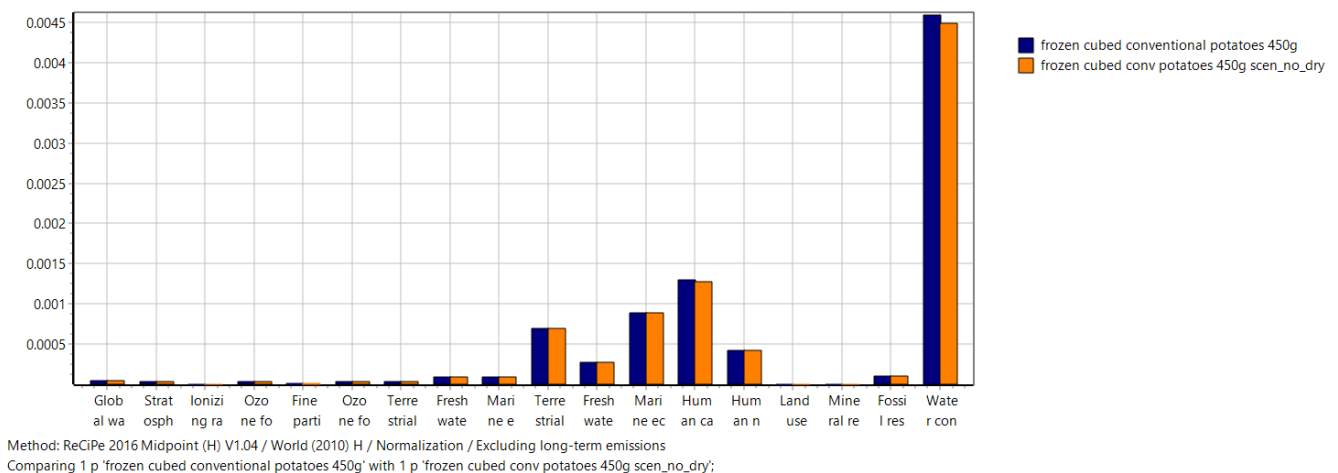


Figure 9. Normalisation results for conventional potatoes scenario comparison between the base scenario and the scenario of lower required irrigation quantities (“scen_no_dry”). Source: [58].

The organic system of the second new scenario presents a reduction for almost all environmental impact categories apart from ionising radiation, freshwater and terrestrial ecotoxicity, and mineral resource scarcity (Figure 10), thus confirming the importance of moving towards renewable resources for the firm under study. Regarding the three most influenced environmental impact categories, water consumption experienced a 17.06% decrease, human carcinogenic toxicity 24.81%, whilst terrestrial ecotoxicity saw an increase of 5.5%.

In a similar way, the conventional system of the “scen_renew” scenario presents a better performance for almost all environmental impact categories, except for ionising radiation, terrestrial and freshwater ecotoxicity, and mineral resources scarcity (Figure 11). As with the case for organic potatoes, the conventional system demonstrates a decrease of 16.45% in terms of water consumption, 24.5% for human carcinogenic toxicity, and 0.49% for marine ecotoxicity.

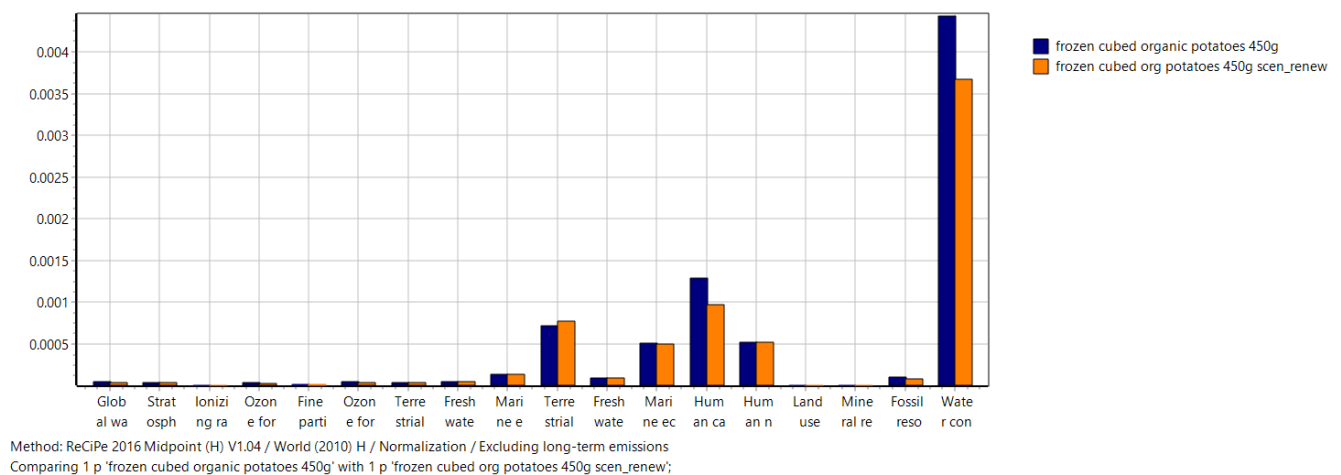


Figure 10. Normalisation results for organic potatoes scenario comparison between the base scenario and the scenario of 50% energy from renewables (“scen_renew”). Source: [58].

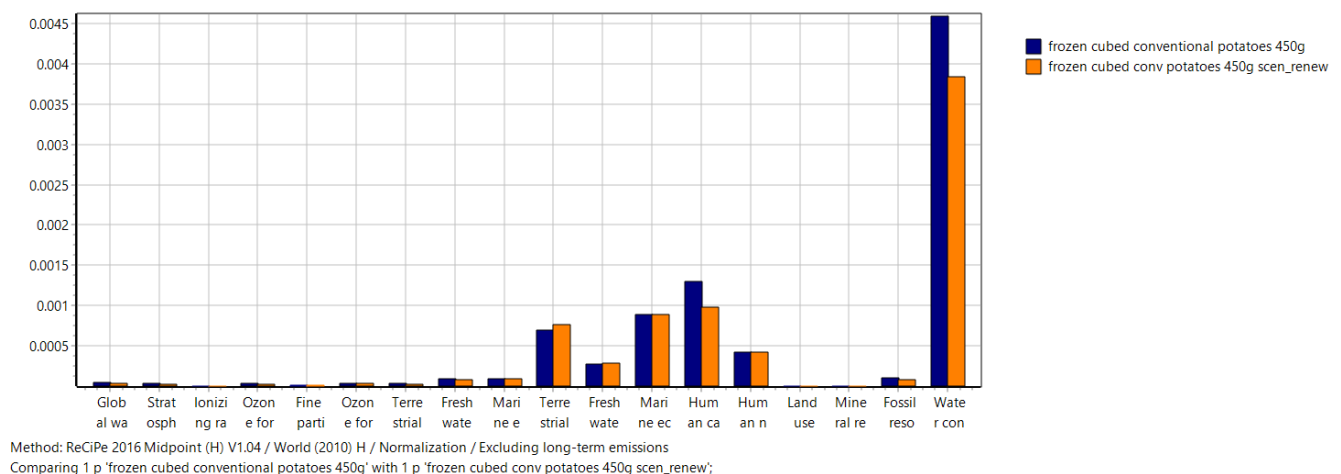


Figure 11. Normalisation results for conventional potatoes scenario comparison between the base scenario and the scenario of 50% energy from renewables (“scen_renew”). Source: [58].

4.1.4. Parallel Analysis of the Finished Product Under Organic and Conventional Production Systems

Figure 12 shows the normalisation results for both types of potatoes. As also reported in Table 9, the trend is consistent with the previously analysed comparison of the agricultural phases in the two production systems. The industrial stage is similar in both cases, with the only difference being the use of chlorinated water for line disinfection prior to processing in the organic system.

The way the characterisation results of the finished product vary across the most influenced impact categories will be analysed. As previously discussed, the most influenced category in both production systems is water consumption. As reported in Tables 3 and 6, the main contributing processes are the same in both systems. Due to the similarity of the processing operations, the impacts associated with these stages are the same (industrial phase electricity and packaging).

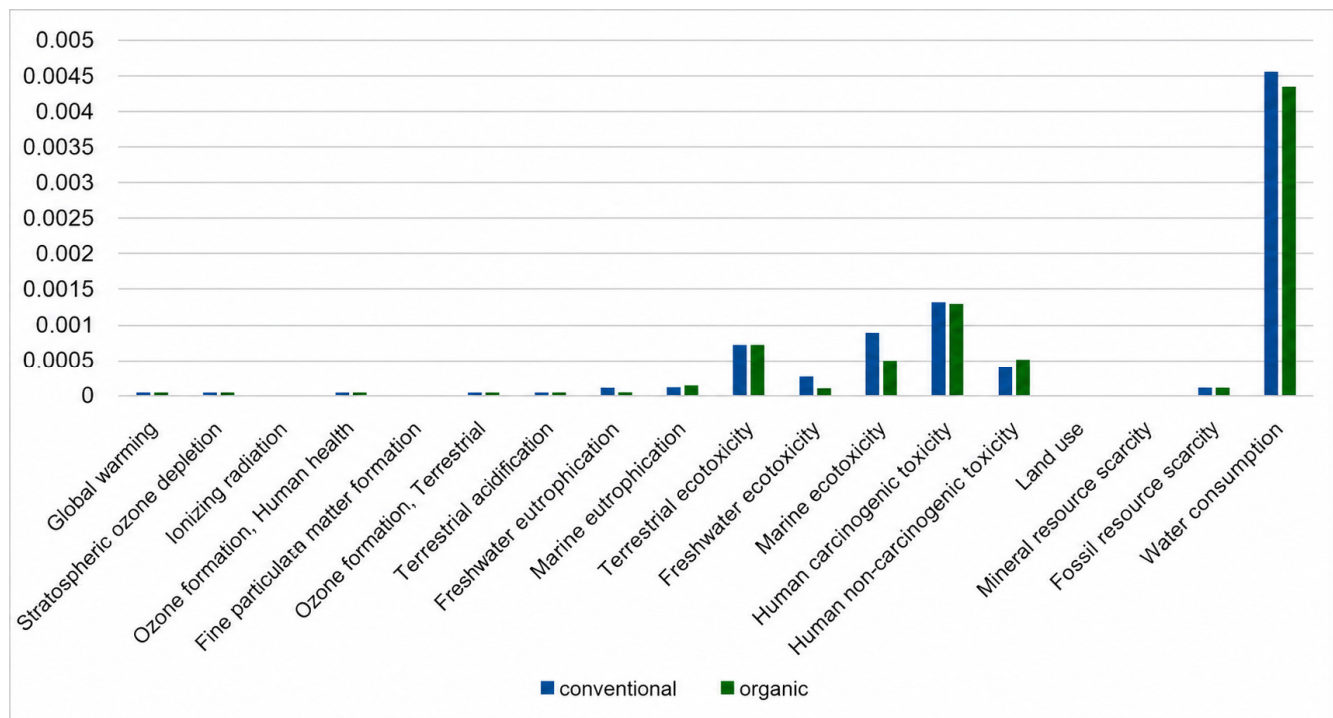


Figure 12. Normalised results for organic and conventional potatoes. Source: own elaboration based on data from SimaPro [58].

Table 9. Characterisation results for both types of potatoes, including the agricultural, processing, and packaging phases. Source: [58].

Impact Category	Unit of Measure	Organic	Conventional
Global warming	kg CO ₂ eq	0.376085123	0.351035631
Stratospheric ozone depletion	kg CFC ₁₁ eq	2.25878×10^{-6}	1.71123×10^{-6}
Ionising radiation	kBq Co-60 eq	0.001623837	0.001639091
Ozone formation, human health	kg NO _x eq	0.00068441	0.000658793
Fine particulate matter formation	kg PM2.5 eq	0.000417583	0.000417363
Ozone formation, terrestrial ecosystems	kg NO _x eq	0.000702134	0.000675947
Terrestrial acidification	kg SO ₂ eq	0.001491147	0.001418498
Freshwater eutrophication	kg P eq	3.06405×10^{-5}	5.67782×10^{-5}
Marine eutrophication	kg N eq	0.000603558	0.000441205
Terrestrial ecotoxicity	kg 1,4-DCB	0.735018867	0.72418451
Freshwater ecotoxicity	kg 1,4-DCB	0.000110573	0.000341972
Marine ecotoxicity	kg 1,4-DCB	0.000517695	0.000922223
Human carcinogenic toxicity	kg 1,4-DCB	0.003564253	0.003607668
Human non-carcinogenic toxicity	kg 1,4-DCB	0.07717141	0.062243332
Land use	m ² a crop eq	0.02908921	0.009774502
Mineral resource scarcity	kg Cu eq	0.000308457	0.000380058
Fossil resource scarcity	kg oil eq	0.101195594	0.100260739
Water consumption	m ³	1.180978761	1.224011116

Irrigation-related impacts are higher in the conventional system, suggesting that the greater water demand—and consequently the associated energy consumption for pumping—is not offset by higher yields.

In the case of compost (within the liquid digestate), although the same quantity per hectare was used, the associated impact is higher for the organic system. This may indicate a dependence on yield differences, suggesting that a higher productivity of the conventional system can partially offset these effects.

The second most affected impact category is human carcinogenic toxicity, with total values of 0.00356 kg 1,4-DCB for the organic system and 0.00361 kg 1,4-DCB for the conventional system. The two results are very similar, and the same applies to the processes that are deemed responsible for this impact category.

Moreover, electricity use in processing and packaging has similar effects in both systems, while differences between the two types of products are mainly related to the agricultural phase, particularly due to higher water consumption in the conventional system.

A similar contribution is observed for the terrestrial ecotoxicity impact category (the third most influenced for organic potatoes). As shown in Table 10, 54.42% of the total impact is attributable to the energy required for the industrial phase. A comparable contribution is associated with the two types of seed used; however, the impact of copper in the organic system is approximately twice that of the conventional system. It is to be noted here that, as mentioned in Section “Agricultural Phase”, generic copper was used in the software for the calculations because 100% regenerated national copper was unavailable in the database. This entails that the impact of copper is actually lower than the one measured and demonstrated in Table 10.

Table 10. Characterisation results for both types of potatoes, including the agricultural, processing, and packaging phases, for the “Terrestrial ecotoxicity” impact category. Source: [58].

Terrestrial Ecotoxicity			
Organic		Conventional	
Processes	Total (kg 1,4-DCB)	Processes	Total (kg 1,4-DCB)
Total of all processes	0.735	Total of all processes	0.724
Electricity (industry)	0.401	Electricity (industry)	0.4
Copper oxide	0.12	Conventional seed	0.122
Organic seed	0.118	Copper oxide	0.0586
Tap water	0.0173	Tap water	0.0227
Transport	0.0164	Phosphate fertiliser	0.0207

Finally, for the case of marine ecotoxicity (the third most influenced for the conventional system), a lower impact is observed in the organic system (43.8% less than the conventional system). A substantial portion of this difference is attributable to the conventional seed, which exerts an impact approximately four times higher than that of the organic seed within this category (Table 11).

Such analyses clearly indicate that the majority of environmental impacts are attributable mainly to the agricultural phase and refrigeration. As evidenced by the reported percentages, more than 60% of the total impacts originate from these two stages, identifying them as the primary intervention points for improving the overall environmental performance of the products under study.

Table 11. Characterisation results for both types of potatoes, including the agricultural, processing, and packaging phases, for the “Marine ecotoxicity” impact category. Source: [58].

Marine Ecotoxicity			
Organic		Conventional	
Processes	Total (kg 1,4-DCB)	Processes	Total (kg 1,4-DCB)
Total of all processes	0.000518	Total of all processes	0.000922
Electricity (industry)	0.000242	Conventional seed	0.000476
Organic seed	0.000117	Electricity (industry)	0.000242
Copper oxide	5.57×10^{-5}	Phosphate fertiliser	3.48×10^{-5}
Diesel	2.4×10^{-5}	Copper oxide	2.73×10^{-5}
Film LDPE (packaging)	2.11×10^{-5}	Magnesium oxide	2.35×10^{-5}

In the assessment, the initial refrigeration stage was associated with electricity consumption, and consequently with the environmental burdens linked to both its use and generation. Its significant contribution across almost all impact categories suggests that mitigation strategies should focus not only on reducing the overall energy consumption but also on improving the electricity mix. The introduction, for example, of renewable energy by industrial-stage companies (e.g., photovoltaics) or an improved storage mechanism would help mitigate this impact (e.g., [68]). This also highlights the importance stated in the Introduction of including post-harvest and industrial phases in the assessment and not just the agricultural one.

On the other hand, the agricultural phase involves a more complex set of interconnected inputs. As previously demonstrated, the main contributors to its impacts are seed production, irrigation water use, and the associated energy consumption for pumping, as well as the application of fertilisers, fungicides, and other agrochemical inputs.

4.2. Social Risk Assessment

Across both the agricultural and processing phases of potato production, the main social issues are related by the “Health and Safety” category, followed by “Labour Rights and Decent Work”, “Society”, “Governance”, and “Community”, emerging as the most significant contributor to the overall social risk.

Table 12 summarises the risk levels for each indicator in the Risk Mapping Tool by impact category and subcategory, with reference to the sectors corresponding to the agricultural and industrial phases.

Table 12. List of risk levels per indicator for the two phases under analysis. Source: [69].

Impact Category	Subcategory	Indicator	Agricultural Phase	Industrial Phase
Labour Rights and Decent Work	Wage assessments	Overall country-sector risk that average wage is below the benchmarks	Low risk	Low risk
		Risk that sector average wage is below the living wage	Low risk	Low risk
		Risk that sector average wage is below the sweatfree wage	Low risk	Low risk
		Risk that sector average wage is below the country’s minimum wage	No data	No data

Table 12. Cont.

Impact Category	Subcategory	Indicator	Agricultural Phase	Industrial Phase
Labour Rights and Decent Work	Workers in poverty	Overall risk employed population is living below the international poverty line (1.9 USD)	No data	No data
	Child labour	Overall country-sector risk of child labour	Low risk	Low risk
		Risk of male child labour in country (UNICEF)	No data	No data
		Risk of female child labour in country (UNICEF)	No data	No data
		Risk of total child labour in country (UNICEF)	No data	No data
		Risk of children missing out on childhood (Save the Children)	Low risk	Low risk
		Risk related to children's rights in the workplace (index)	Low risk	Low risk
	Forced labour	Overall country-sector risk of forced labour	High risk	Medium risk
		Risk of trafficking in persons (US DoL)	Medium risk	Medium risk
		Forced labour risk (Global Slavery Index)	Medium risk	Medium risk
		Overall country risk of forced labour	Medium risk	Medium risk
	Excessive working time	Overall risk of excessive working time	Medium risk	Medium risk
		Risk of working > 48 h per week (ILO)	Low risk	Low risk
		Lack of regulatory framework for working hours and its implementation	Medium risk	Medium risk
	Freedom of association, collective bargaining, right to strike	Overall risk related to freedom of association, collective bargaining, right to strike	Low risk	Low risk
		Lack of association and collective bargaining rights and right to strike (ITUC)	Low risk	Low risk
		Collective bargaining coverage (ILO)	Low risk	Low risk
	Migrant Labour	Overall risk migrant workers	High risk	High risk
		Net migration rate	High risk	High risk
		Workers' remittances and compensation paid per immigrant	Low risk	Low risk
		Ratified international conventions or set up policies for immigrants	Low risk	Low risk
		Immigrants as a percentage of the population	High risk	High risk
		Evidence of risk to migrant workers—qualitative	High risk	High risk
		People of concern	Medium risk	Medium risk
		Overall risk social benefits	Medium risk	Medium risk
	Social benefits	Paid annual leave available to workers	Low risk	Low risk
		Sick leave (pay, start, duration)	Medium risk	Medium risk
		Maternal leave (pay and duration)	Medium risk	Medium risk
		Paternal leave (pay and duration)	Medium risk	Medium risk
		Parental leave (pay and duration)	Medium risk	Medium risk
		Other types of leave (child, adult, educational and health)	Low risk	Low risk
		Proportion of population covered by social assistance programmes	No data	No data

Table 12. Cont.

Impact Category	Subcategory	Indicator	Agricultural Phase	Industrial Phase
Labour Rights and Decent Work	Labour laws and conventions	Overall risk labour laws and conventions	Medium risk	Low risk
		Year minimum wage was last updated	Medium risk	Medium risk
		Number of labour laws in country	Low risk	Low risk
		Number of labour laws by sector	Low risk	Low risk
		Ratification of ILO Conventions	Medium risk	Medium risk
		Ratification of conventions by sector	Medium risk	Low risk
	Discrimination and equal opportunity	Overall prevalence of discrimination in the workplace (qualitative)	Medium risk	Medium risk
	Unemployment	Overall (un)employment risk	High risk	High risk
		Unemployment level	Very high risk	Very high risk
		Vulnerable employment	Medium risk	Medium risk
		Unemployment programmes in place (ISSA)	Low risk	Low risk
Health and Safety	Occupational toxics and hazards	Overall risk occupational toxics and hazards	High risk	High risk
		Occupational noise related risk	Low risk	Low risk
		Occupational cancer-related risk	Very high risk	Very high risk
		Occupational asthma related risk	Low risk	Low risk
		Occupational COPD related risk	Very high risk	Very high risk
		Occupational pneumonia related risk	Medium risk	Medium risk
		Occupational infectious disease related risk	Low risk	Low risk
	Occupational injuries and fatalities	Overall risk of occupational injuries and fatalities	Medium risk	Medium risk
		Occupational road injury- and fatality-related risks	Low risk	Low risk
		Occupational poison-related injuries and fatalities	Low risk	Low risk
		Occupational-related fall injuries and fatalities	Very high risk	Very high risk
		Occupational-related fire/heat injuries and fatalities	Low risk	Low risk
		Occupational-related drowning injuries and fatalities	Low risk	Low risk
		Occupational-related exposure to mechanical forces injuries and fatalities	Medium risk	Medium risk
Society	Indigenous rights	Overall country-sector risk related to indigenous rights infringement	No evidence	No evidence
		Overall country risk of indigenous rights being infringed	No evidence	No evidence
		Percent of population that is indigenous	No evidence	No evidence
		Ratification conventions to protect indigenous rights	No evidence	No evidence
		Number of laws to protect indigenous rights (ILO)	No evidence	No evidence
	Gender Equality	Overall gender equality risk	Low risk	Low risk
		Social Institutions and Gender Index (SIGI)	Low risk	Low risk
		The Global Gender Gap Index (World Economic Forum)	Medium risk	Medium risk
		Gender Inequality Index (GII) (UNDP)	Low risk	Low risk
		Women, Business, and Law Index (World Bank)	Low risk	Low risk

Table 12. Cont.

Impact Category	Subcategory	Indicator	Agricultural Phase	Industrial Phase
Society	High conflict zones	Overall risk of high conflict	Medium risk	Medium risk
		High conflict (Heidelberg Institute)	No evidence	No evidence
		State Fragility Index (Centre for Systemic Peace)	High risk	High risk
		People under Threat (Minority Rights Group)	No data	No data
		Global Peace Index	Low risk	Low risk
	Human health issues—non-communicable diseases (NCD) and other health risks	Overall risk of non-communicable diseases and other health risks	Low risk	Low risk
		Life expectancy at birth (years)	Low risk	Low risk
		Under-five mortality rate	Low risk	Low risk
		Age-standardised mortality rates for non-communicable diseases	Low risk	Low risk
		Age-standardised mortality rates for injuries	Low risk	Low risk
		Proportion of undernourished in population	Low risk	Low risk
		Age-standardised mortality for cardiovascular diseases	Low risk	Low risk
		Mortality rate attributed to household and ambient air pollution and exposure to unsafe WASH services	Low risk	Low risk
		Population affected by natural disasters	Low risk	Low risk
		Overall risk: human health issues—Communicable diseases, age-standardised mortality rates from communicable diseases.	Low risk	Low risk
		Cases of HIV	Low risk	Low risk
		Cases of tuberculosis	Low risk	Low risk
		Notified cases of malaria	No data	No data
		Dengue fever, incidence rate	No data	No data
Governance	Legal system	Overall risk of fragility in legal system	Medium risk	Medium risk
		Worldwide Governance Rule of Law Indicator (World Bank)	Medium risk	Medium risk
		Rule of Law—Independent Judiciary (Bertelsmann Transformation Index)	No data	No data
		Rule of Law Index (World Justice Project)	Medium risk	Medium risk
		Rule of Law—Independent Judiciary (Bertelsmann Transformation Index)	No data	No data
	Corruption	Overall risk of corruption	Medium risk	Medium risk
		Worldwide Governance Indicators Corruption Index (World Bank)	Medium risk	Medium risk
		Corruption (Competitiveness report WEF)	Medium risk	Medium risk
		Corruption Perception Index (CPI) (Transparency International)	Medium risk	Medium risk
		CPI 3-year trend (2017–2020) (Transparency International)	Low risk	Low risk

Table 12. Cont.

Impact Category	Subcategory	Indicator	Agricultural Phase	Industrial Phase
Governance	Democracy and freedom of speech	Overall risk related to democracy and freedom of speech	Medium risk	Medium risk
		Democracy Index (EUI)	Medium risk	Medium risk
		Freedom of speech (Freedom House)	Low risk	Low risk
		Global State of Democracy indices (IDEA)	Medium risk	Medium risk
Community	Access to improved source of drinking water	Overall access to improved source of drinking water	Low risk	Low risk
		Urban access to improved source of drinking water	Low risk	Low risk
		Rural access to improved source of drinking water	Low risk	Low risk
	Access to improved source of sanitation	Overall access to improved source of sanitation	Low risk	Low risk
		Urban access to improved source of sanitation	Low risk	Low risk
		Rural access to improved source of sanitation	No data	No data
	Children out of school	Children out of school	Low risk	Low risk
		Children out of primary school, male	Low risk	Low risk
		Children out of primary school, female	Low risk	Low risk
	Access to health care	Overall risk related to access to health care	Medium risk	Medium risk
		Hospital beds	Low risk	Low risk
		Nurses/Midwives	High risk	High risk
	Smallholders versus commercial farms (only agriculture sectors)	Overall risk related to (agri) smallholders	Medium risk	No evidence
		Percentage of family-owned farms in country	Medium risk	No evidence
		Percentage of commercially owned farms in country	Medium risk	No evidence
		Smallholdings land % > x hectares	Low risk	No evidence
	Access to electricity	Overall access to electricity	Low risk	Low risk
	Property rights	Overall property rights (citizen's perceptions)	Low risk	Low risk

Figure 13 presents the distribution of social risk levels for the agricultural and industrial phases, expressed as the number of indicators at the same risk level. Overall, the two phases show a very similar risk profile, with only minimal differences between them in relation to sector-level indicators. The largest share of indicators falls within the low risk level, with 54 indicators for the agricultural and 55 for the industrial phase, indicating that most of them do not reveal critical social issues.

A relevant proportion is also classified as medium risk: 29 indicators in the agricultural and 28 in the industrial phase. This suggests the presence of areas that require monitoring and possible preventive actions, although they do not represent the most critical hotspots. The high-risk group includes eight indicators in the agricultural and seven indicators in the industrial phase, whilst the very-high-risk level is limited to four for both phases. These results indicate that the most severe social risks are relatively concentrated, but they remain important because they identify priority areas for intervention.

Furthermore, Figure 13 also shows the presence of no evidence and no data indicators, with 6 and 12 indicators, respectively, for both phases. This aspect is particularly relevant because the absence of evidence or data may limit the robustness of the assessment. Therefore, these categories should not be overlooked, as they point to areas where additional data collection or further investigation would be needed.

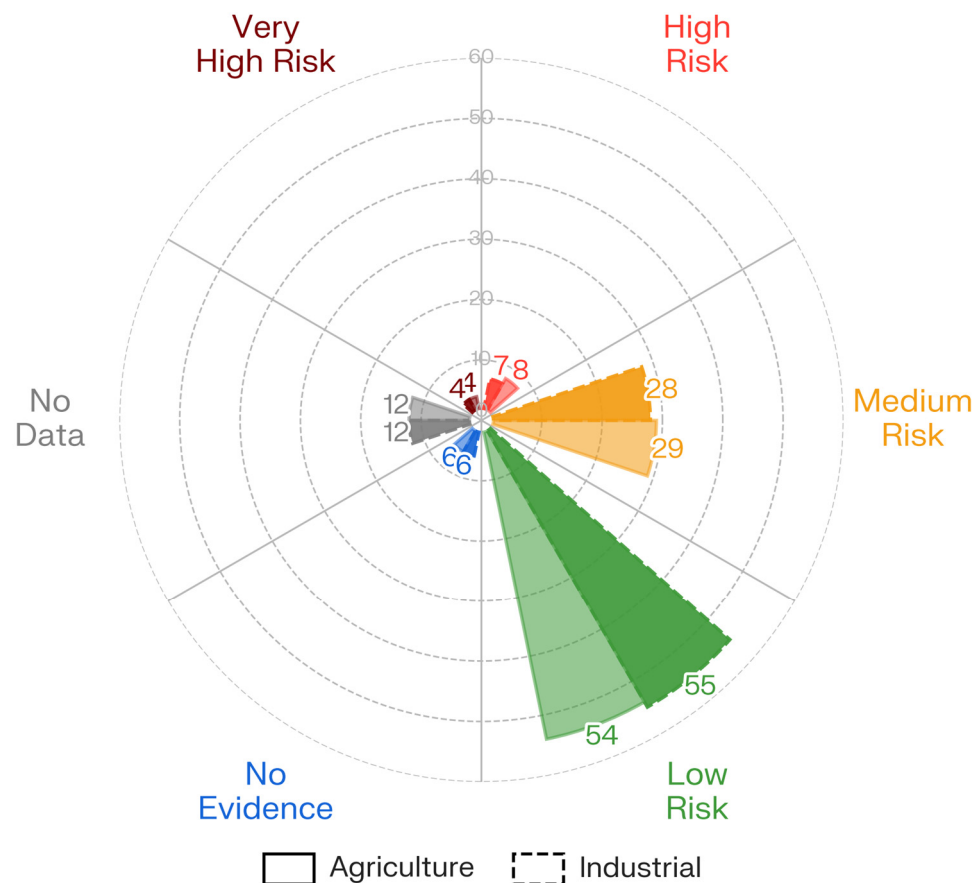


Figure 13. Social risk assessment map of indicators aggregated per risk level. Elaborated by the authors and supported by AI.

In more detail, the “Health and Safety” category encompasses the “Occupational Toxics and Hazards” and the “Occupational Injuries and Fatalities” subcategories. The former covers a wide range of risks arising from human exposure to diverse workplace hazards, such as excessive noise, carcinogenic substances, and airborne particles capable of causing respiratory or other diseases, in addition to two sector-specific risks: particulate exposure in coal mining and needlestick injuries among healthcare personnel [61]. On the other hand, the latter considers injuries resulting from an accident arising out of or in the course of employment, including commuting, which may lead to death, personal harm, or illness involving loss of working time [61]. Both subcategories are assessed using country-level indicators. The overall risk related to “Occupational Toxics and Hazards” is high, while that associated with “Occupational Injuries and Fatalities” is assessed as medium. However, when considering individual indicators, a very high risk is identified for fall-related occupational injuries and fatalities, as well as for occupational chronic obstructive pulmonary disease (COPD) and occupational cancer-related risk.

However, further investigation of the context, supported by additional sources, revealed that, within the European Union in 2023, Italy recorded a fatal injury rate broadly in line with the EU-27 average, while for non-fatal injuries, it has recorded values consistently below the European average over recent years [70]. Regarding work-related diseases, provisional 2025 data show an 11.3% increase in reported cases compared to the previous year and confirm that the most prevalent conditions are those affecting the musculoskeletal system and connective tissue, followed by diseases of the nervous system and those of the ear and mastoid process, while tumours, respiratory diseases, and other conditions

remain less frequent and show more variable trends [70]. Moreover, 68.7% of reported cases concern workers in the agricultural sector [70].

When it comes to the “Labour Rights and Decent Work” category, the results highlight that the social themes related to protection of labour rights and the promotion of decent working conditions are particularly exposed to risk both at the country and sector levels.

In particular, at the country level, there is a high overall risk of unemployment and related to migrant workers, while risks related to excessive working time, workplace discrimination, and access to social benefits are assessed as medium. The subcategories “Wage Assessments” and “Freedom of Association, Collective Bargaining, and the Right to Strike” do not present significant critical issues, as their overall risks are low. Similarly, “Child Labour” does not show critical concerns (although data for some indicators are missing): the overall country-sector risk is low.

At the sector-specific level, the overall risk of forced labour is high in activities related to the agricultural phase, and medium in those associated with the industrial phase. Similarly, the overall risk related to labour laws and conventions is assessed as medium in agricultural activities, while it is considered low in the industrial phase.

Indeed, across the entire national territory, there is a widespread pattern of non-compliance with regulations governing working hours, wages, social security contributions, entitlement to paid leave, occupational health and safety, and the provision of decent working conditions [71].

In particular, illegal practices are prevalent in the recruitment, placement, and organisation of labour [71,72], especially targeting vulnerable groups such as migrants, women, and minors [71].

Sectors that rely more heavily on foreign labour also tend to be the most vulnerable to distortions in employment relationships, where irregular and undeclared work are particularly common [71]. In Italy, the overall rate of labour irregularity is 12.7%, increasing to 17.6% in the agricultural sector [71].

Child labour remains a pervasive phenomenon, although it is still largely hidden and underreported [73]. An estimated 336,000 minors aged 7 to 15, corresponding to 6.8% of the population in this age group, have had work experience before reaching the legal working age [74]. Around 5.7% of minors who have engaged in work activities have a migrant background. Agricultural activities account for 9.1% of cases affected by the phenomenon [74].

Child labour has a negative impact on learning, reducing the time available for study and thereby contributing, in many cases, to school disengagement and early dropout [74]. In nearly one out of two cases (40.4%), work negatively affects educational opportunities, and 14–15-year-old working students are almost twice as likely to have been held back a grade compared to their peers who have never worked [74]. Temporary school interruptions are also more than twice as frequent among working students [74].

These considerations should be taken into account in interpreting the results, especially given that the overall risk of children out of school has been assessed as low in the “Community” category.

The “Labour Rights and Decent Work” category also includes the subcategory “Workers in Poverty”, for which, however, no data are available for the relevant indicator. In this regard, it is also worth noting that in Italy, 2.2 million households are living in absolute poverty, equivalent to 8.4% of all resident households, for a total of 5.7 million individuals [75].

In the “Society” category, the overall risk related to gender equality is low, as is the overall risk associated with both non-communicable and communicable diseases.

By contrast, the risk related to high levels of conflict is assessed as medium. This is largely driven by the State Fragility Index (SFI) [76], which classifies each country by its degree of fragility in terms of both effectiveness and legitimacy [61].

In the “Governance” category, the overall risk is assessed as medium with regard to fragility in the legal system, corruption, democracy, and freedom of speech.

The risk of legal system fragility is based on the Rule of Law indicator within the Worldwide Governance Indicators, which measures governance across six dimensions: “Voice and Accountability”, “Political Stability government effectiveness”, “regulatory quality”, “Rule of Law”, and “Control of Corruption” [77]. It also draws on the “Rule of Law—Independent Judiciary” indicator from the Bertelsmann Transformation Index, which “analyses transformation processes towards democracy and a market economy in international comparison, identifying successful strategies for peaceful change” [78].

The subcategory “Democracy and Freedom of Speech” shows a medium level of risk across its individual indicators. This includes the Democracy Index (EIU), which measures the state of democracy in 167 countries and territories by assessing electoral processes, government functioning, political participation, political culture, and civil liberties [79].

Finally, a medium risk is recorded for corruption-related indicators, including the Worldwide Governance Indicators—Corruption Index [80], the corruption component of the World Economic Forum Competitiveness Report [81], and the Corruption Perception Index [82].

Finally, the remaining subcategories within the “Community” category do not present any significant critical issues, with an overall low risk across all subcategories. An exception is “Access to Health Care”, which presents an overall medium risk, with a high risk associated in particular with the “Nurses/Midwives” indicator. Indeed, in Italy, general practitioners are in decline, and shortages of staff are also reported in emergency and urgent care services. The gap in the number of nurses compared to the European average exceeds 180,000 units [83].

Another exception is represented by a medium level of risk associated with smallholders, who are understood not as a separate stakeholder group, but as a subcategory consistent with the Social LCA Guidelines [28] and the Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021 [84].

In Italy, small-scale farms are currently facing a particularly challenging context. Between 2007 and 2022, Italy lost 37% of its farms. This decline has mainly affected small-scale holdings, which decreased by 51%. Nevertheless, they continue to represent the backbone of Italian agriculture, accounting for 65% of farms, although they receive only 31% of the available subsidies [85].

4.3. Limitations

As far as the environmental dimension is concerned, the main limitations of this study regard the agricultural phase in terms of its modelling on the software. In more detail, these concern the fact that in some cases, some phytosanitary products were not available in the software databases, and only their packaging (and its end of life) was taken into account. This can, however, be regarded as marginal because the non-considered products were of natural origin. It should be, furthermore, noted that in this study, for copper-based fungicides, 100% regenerated copper of national origin was used; however, it was not considered as it was unavailable in the database, and instead, a generic copper was selected.

With regard to the social dimension, some limitations should be acknowledged, which are partly related to the methodological choices adopted in this study. The performed mapping enabled quick and intuitive identification of the social risks associated with potato

production in Italy. Such a screening approach enabled the initial identification of the main risk areas, laying the groundwork for a subsequent targeted in-depth analysis. Indeed, it can support prioritising data collection by identifying aspects that require further investigation through site-specific data acquisition [28]. On the other hand, a risk assessment can help determine which social aspects cannot be excluded from the case study [31].

In this context, the results will serve as a basis for further investigation, enabling the identification of social aspects that would benefit from a more detailed analysis through an S-LCA study based on site-specific data to assess social performance (a Social Life Cycle Performance Assessment in accordance with ISO 14075:2024 [31]).

Moreover, the resulting risk levels can also serve as an additional evaluation parameter for enterprises, acting as a benchmark for a more in-depth and meaningful interpretation of their performance [86].

Furthermore, the adopted mapping approach has limitations stemming from the structure of the database and the underlying global input/output model. In particular, the sector-based classification entails a loss of granularity with respect to specific economic activities associated with individual products, as heterogeneous operations are often included into a single sector [87]. With regard to the specificity of the results, it should also be noted that many indicators are available only at the country level rather than at the sector level. Regarding the sectoral dimension, the agricultural and industrial phases were treated as distinct sectors, as interconnections between them could not be established. Finally, several indicators remain affected by data gaps. In this sense, integrating the results with additional sources has enabled a clearer understanding of the findings, identifying the areas that require further in-depth analysis with particular reference to the sector under investigation, namely health and safety and working conditions. Regarding the integration of the results, the environmental and social dimensions are discussed in parallel rather than within a fully integrated assessment framework. Meaningful integration remains challenging due to fundamental methodological differences between the approaches adopted [88]. The assessments address distinct sustainability dimensions and generate outcomes based on different indicators, measurement scales, units of analysis, and evaluation outputs [88]. In particular, the social assessment identifies risk levels, whereas the environmental assessment quantifies potential impacts. Consequently, no common metric is available to support the direct aggregation or comparison of results across dimensions [88]. Nevertheless, the parallel examination of the findings enables the identification of convergences and divergences between environmental hotspots and social risk areas, while recognising the inherent limitations associated with cross-dimensional integration.

5. Conclusions

Current agricultural practices represent a threat to the environment, and the transition towards a more sustainable agriculture is considered to be essential for achieving sustainability objectives. Organic agriculture is generally believed to decrease, in general, the environmental impact; however, its impact may appear higher when mass-based functional units are used instead of area-based ones.

This study applied Life Cycle Thinking methodologies and assessed, in parallel, the environmental and the social aspects of both organic and conventional potatoes, including not only the agricultural phase but also the industry-based one. It is to be highlighted that given the specific characteristics of the two systems under analysis, the results cannot be generalised to all potato production systems.

The most influenced impact category is water consumption; the dominant contributor is the refrigeration stage, understood as the electricity consumption required for its operation. The second most affected category for the finished product is human carcino-

genic toxicity, with very similar results between the two systems. The main contributor is electricity consumption during processing (77% in the organic system and 75.9% in the conventional system), particularly refrigeration, which is the most energy-intensive stage.

Since similar patterns are observed in other impact categories, such as marine and terrestrial ecotoxicity, where electricity consumption during processing is again the dominant driver, particularly due to refrigeration, increasing the share of renewable energy in both the national energy mix and industrial supply could significantly improve the environmental performance of the system.

Enhancing synergies and material and energy exchanges among all stakeholders to create closed-loop systems could also become advantageous, both environmentally and economically. The present system under study already partially operates in a circular manner, where purified industrial water is reused for field irrigation, and liquid digestate is applied as fertiliser: organic residues from the industrial phase are reintegrated into the system through a biogas plant, which, in turn, supplies digestate to farmers. This system could be further improved by providing heat and energy not only to industrial facilities but also to agricultural operations (e.g., greenhouse heating). The circularity of such systems could then be calculated by using agri-food specific circularity indicators.

The use of liquid digestate enables farmers to fertilise fields, allowing field operations at an earlier stage, even under mountainous region-related climatic constraints, where conventional manure application may be limited. Given the environmental impacts associated with fertilisers and their related emissions, more targeted nutrient application strategies aligned with crop needs would be environmentally advantageous.

The agricultural phase emerged as both the primary environmental hotspot and the phase associated with the highest social risks.

Indeed, it stands out as the most critical stage from an environmental perspective, as it is associated with substantial impacts resulting from irrigation, seed production, fertiliser application, and agrochemical inputs. By contrast, the industrial phase is primarily characterised by environmental impacts related to energy consumption and processing activities.

Furthermore, from a social perspective, both phases appear to be socially relevant due to labour-related risks that are characteristic of the Italian context, although the overall social risk profile of the industrial phase is comparatively less pronounced than that of the agricultural one. Therefore, while the environmental and social hotspots do not fully coincide, both phases emerge as important areas of concern from a sustainability perspective.

In particular, with regard to the social dimension, the risk assessment highlighted that, in the context of potato production, both the agricultural and industrial phases present social risks that are mainly related to the “Health and Safety” category. Indeed, the “Health and Safety” category is the main contributor to the overall social risks, followed by “Labour Rights and Decent Work”, “Society”, “Governance”, and “Community”. The analysis of results by risk level shows a prevalence of low- and medium-risk-level indicators, suggesting an overall moderate level of social criticality. Nevertheless, the presence of high-risk and very-high-risk indicators identifies specific social hotspots that require targeted monitoring actions.

The specific risks identified through the Risk Mapping Tool were subsequently interpreted, considering the Italian context, by examining additional information from other sources (e.g., reports by Save the Children, Greenpeace, the Ministry, and ISTAT) to enable a more accurate and robust interpretation. The resulting picture indicates that the Italian agri-food sector remains particularly critical, especially with respect to working conditions, due to the widespread occurrence of labour exploitation and non-compliance with regulations governing working hours, wages, social security contributions, entitlements to paid leave, occupational health and safety, and the provision of adequate working conditions.

In terms of implications, mapping social hotspots through a social risk assessment is essential for identifying areas where the most significant social risks are concentrated. This allows decision-makers to go beyond a generic assessment and focus their attention, resources, and corrective actions on the most critical indicators, activities, or life cycle phases. In this sense, social risk assessment fosters more effective governance, improves the prioritisation of interventions, and provides a solid basis for developing strategies aimed at reducing social risks and improving social performance. Nevertheless, the findings obtained should be considered as a preliminary screening for providing the basis for a subsequent S-LCA study to evaluate the social performance of the companies involved in the production of the product under analysis.

A social performance assessment enables a more effective integration of the results, particularly in supporting the adoption of responsible and sustainable practices. In this regard, the evaluation of all dimensions of sustainability becomes essential to ensuring a comprehensive understanding of system performance and to inform decision-making processes.

Future research would move towards using circularity indicators for measuring the circularity of the system. Moreover, given the scarcity of studies addressing the agricultural, processing, and packaging phases of potato production in the literature, future research could integrate not only the environmental and social dimensions but also the economic ones via a dedicated LCC study. Finally, more potato systems could be analysed in parallel in order for the robustness of the results to be verified.

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