

Article

Life Cycle Assessment of Spinach Produced in Central and Southern Italy

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Abstract: Environmental sustainability continues to attract global interest, especially due to the issue of climate change. The agri-food sector is considered a major contributor to climate change as processes and activities within the sector can negatively impact the environment. The recent changing dietary pattern towards increased vegetable consumption implies a consequent increase in production to meet demand. This study assessed the environmental performance of 1 kg of spinach/FU (Functional Unit) cultivated by different producers in Italy under integrated and organic farming systems. The life cycle assessment was used following the CML_IA impact assessment method. The data used was mainly primary, related to 2019/2020 (harvest period), and representative of the cultivation systems of central and southern Italy. From the results obtained, impact scores for central Italy were higher (e.g., for global warming 0.56 and 0.47 kg CO₂ eq. for central and southern respectively). There was high variability among the scores obtained. However, no statistically significant differences were observed at a confidence level of 95% ($p < 0.05$). Integrated farming was also more impacting than organic for most categories (e.g., for global warming 0.20 kg CO₂ eq. for integrated and 0.075 kg CO₂ eq. for organic) in Cerignola, Puglia region. Emissions from fertilizer, pesticide, tillage, and combine harvesting were major contributors to impact shares. The results of this study will be helpful to ensure sustainable spinach production and consumption.

Keywords: sustainability; environment; frozen spinach; impact assessment; emissions; organic farming; integrated farming



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1. Introduction

Sustainability in the context of agriculture refers to activities that meet current and future societal needs for food and feed, ecosystem services, and healthy lives with a net positive benefit to society when all costs and benefits of the activities are taken into consideration [1]. Meeting the needs of an increasing global population implies an increase in food and feed production which can negatively impact the environment regarding greenhouse gas emissions, water, energy, and land use [2]. Environmental sustainability in the agri-food sector has thus, gained significant attention on a global scale in recent times due to its potential direct effect on food production systems [3]. The direct dependence of farming activities on climatic conditions, especially under unprotected production systems, makes agriculture highly vulnerable to climate change [4]. The agri-food sector is one of the primary sectors of global environmental concern. An estimated 23% of total anthropometric greenhouse gas (GHG) emissions is derived from agriculture, forestry, and other land use [5]. Therefore, strengthening the sustainability of food systems towards improved efficiency in production and consumption is highlighted in the 2030 Agenda for Sustainable Development, which seeks to ensure food security, nutrition, and rural transformation on a global scale [6].

Additionally, the European roadmap to Resource Efficiency highlighted several important goals for agriculture, including a 50% reduction in waste production, the preservation

of biodiversity and ecosystem services, the reduction of land use, the improvement in soil quality, and the independence from fossil fuels [7]. The European Common Agricultural Policy (CAP) also aims to promote the development of innovative agricultural practices that protect biodiversity and the preservation and development of 'natural' farming and forestry systems, good water management and use, with low greenhouse gases (GHGs) emissions [8]. As such, this presents an opportunity to advocate for the efficient use of resources in the agri-food sector with a reduced environmental footprint in order to meet the food security and sustainability needs.

Globally, the production and consumption of vegetables have increased steadily due to recent changes in dietary patterns, mainly for health reasons [9]. The demand for vegetables has shifted from just being a mere part of our meals to being essential. An estimated 2.2 million hectares of land in the EU was dedicated to the production of fresh vegetables in 2017, with total production valued at 34.5 billion euros [10]. The vegetable production of Italy and Spain for 2019 was worth 7.2 billion euros and 6.9 billion euros respectively, with both countries representing 37% of the total European production of vegetables [11]. The diverse group of leafy and stalked vegetables such as lettuce, spinach, chicory, artichokes, and endives is known to perform several functions biochemically considering their nutritional values in terms of vitamins and minerals, antioxidant properties as well as their dietary fibre content, which aids in weight control [12].

Spinach (*Spinacia oleracea* L.) is a dark green leafy vegetable of high economic and health importance. It is a rich source of many health-promoting compounds such as minerals, vitamins, phytochemicals, bioactive compounds, and fibre [12]. Due to the high abundance of phenolic compounds such as patulein, spinacetin, glucuronides, and flavonoids, it is considered to have a comparatively high antioxidant capacity among vegetables [13–15]. The concept of consuming foods with functional properties to prevent chronic diseases has gained a lot of interest [16]. Spinach extracts have various functional properties including: antiproliferative, anti-obesity, hypoglycaemic, lipid-lowering, anti-inflammatory, and antioxidant [12,13,17–19].

The emerging demand for spinach has stimulated an increase in the production of leafy vegetables across Europe, specifically from 536,385 tonnes in 2009 to 701,862 tonnes in 2019. According to FAOSTAT [9], Italy produced 99,520 tonnes of spinach in 2019, making it the current second-largest producer in Europe. Spinach can be cultivated under different cultivation systems, mainly in open fields or under protected systems such as greenhouses or high tunnels [15,20]. Although it is essential to increase spinach production, there is also the need to consider possible environmental burdens associated with the cultivation of horticultural crops due to inputs required for production [21]. The general supply chain of spinach in Italy often involves pre-harvest operations such as land selection, variety selection, cultivation, harvesting, and postharvest operations that include cooling/freezing, packaging, transporting, storage, use, and waste disposal. Spinach produced in Italy's southern and central parts are mostly sold as a frozen whole leaf or cut frozen leaves in supermarkets.

The food sector is exceptionally varied, with different phases of production systems resulting in various impacts on the environment. Food supply chains are considered to be intricate with respect to environmental effects [22]. More recently, consumers are showing more interest in the environmental aspects of the products they consume [23]. Therefore, environmental impact assessments must be carefully and accurately carried out on these products, considering the many processes and materials involved [24]. Given this, some tools and methodologies have been developed to help quantify the environmental impacts along various supply chains. The Life Cycle Assessment (LCA) is one of such methodologies, which is a decision-making tool that gives a comprehensive approach for evaluating the environmental impacts of a product during the entire production system [25,26]. The LCA is a good tool to examine the environmental impacts of products quantitatively, estimate the life cycle resources and burdens, and quantify alternatives in product systems. LCA is widely accepted and can be used to evaluate activities and processes along food

supply chains. Many companies are showing interest in applying LCA to their products and may even require LCA data from their suppliers as it can be used to provide additional environmental information to customers [27].

In spinach production, very few studies have been conducted globally to assess its environmental performance. In Japan, Shiina et al. [28] evaluated spinach production under a hybrid protective system where they reported its global warming potential (GWP) to be 2.3 kg CO₂ eq./kg spinach. In addition, Seo et al. [29] reported 0.49 kgCO₂ eq. and 0.29 kgCO₂/kg spinach for production under an integrated system and elevated CO₂ treatment production system, respectively. Frankowska et al. [30] assessed the environmental impacts associated with 56 fresh and processed vegetables consumed in the UK and reported a GWP of 1.7 kg CO₂ eq./kg for spinach. Stoessel et al. [31], after also assessing the impacts associated with fruits and vegetables from a Swiss retailer found the endpoint for climate change ecosystem to range between 3.90×10^{-4} and 9.91×10^{-4} Pt for spinach. However, some of these studies relied on extrapolated secondary data from different regions or countries [30,31]. In contrast, others relied on primary data from pilot studies [28,29], which does not represent a realistic spinach production system.

Producers are moving towards cultivating high-yielding and nutritionally quality spinach crops that have minimal detrimental effects on soil fertility, water and air quality, and biodiversity while using minimum resources. Thus, more environmental sustainability studies must be conducted to identify hotspots along the value chain for improvement. Due to limited LCA studies on vegetable production, this study aims to provide an environmental impact assessment from primary data of actual spinach cultivation systems in Italy. This will encourage sustainable production and distribution.

2. Materials and Methods

Life cycle assessment (LCA) was used to calculate the impacts of 1 kg of harvested spinach leaf, following the ISO 14040/14044 standards. The standard LCA has four inter-related phases, which are generally completed in the following order: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation of results. LCA is an iterative process where the different phases can be repeated until the final objective is met [25,32,33]. As stated by the same standard, the analysis can stop at any stage of the life cycle, but any choice must be justified. The methodology, data, and assumptions of this study are further detailed in the following sections.

2.1. Goal and Scope Definition

The tentative goal of this study is to quantify the environmental burdens associated with the cultivation of spinach in central and southern Italy. The analysis is to help develop a tentative agricultural eco-design for a top spinach processing company. The study also seeks to identify environmentally impacting materials and activities where improvement options could be suggested to help producers/farmers improve the environmental aspects of their natural products. This study also provides information on the ecological performance of spinach cultivation in Italy, which is currently unavailable. The target group for this study includes stakeholders within the spinach value chain: spinach producers, environmental authorities, policymakers, and researchers in the LCA field.

The system boundary encompasses the relevant material input/outputs and energy related to the cultivation of spinach. The defined functional unit (FU), based on which inventory data was normalized for further impact assessment, was 1 kg freshly harvested spinach leaf. As shown in Figure 1, the system boundary covers material inputs such as fertilizers, herbicides, water, and cultivation activities that include tillage, fertilization, irrigation, and harvesting. Transportation and postharvest processes were not considered under the system analyzed because these processes are beyond the company's interest in environmental sustainability assessment.

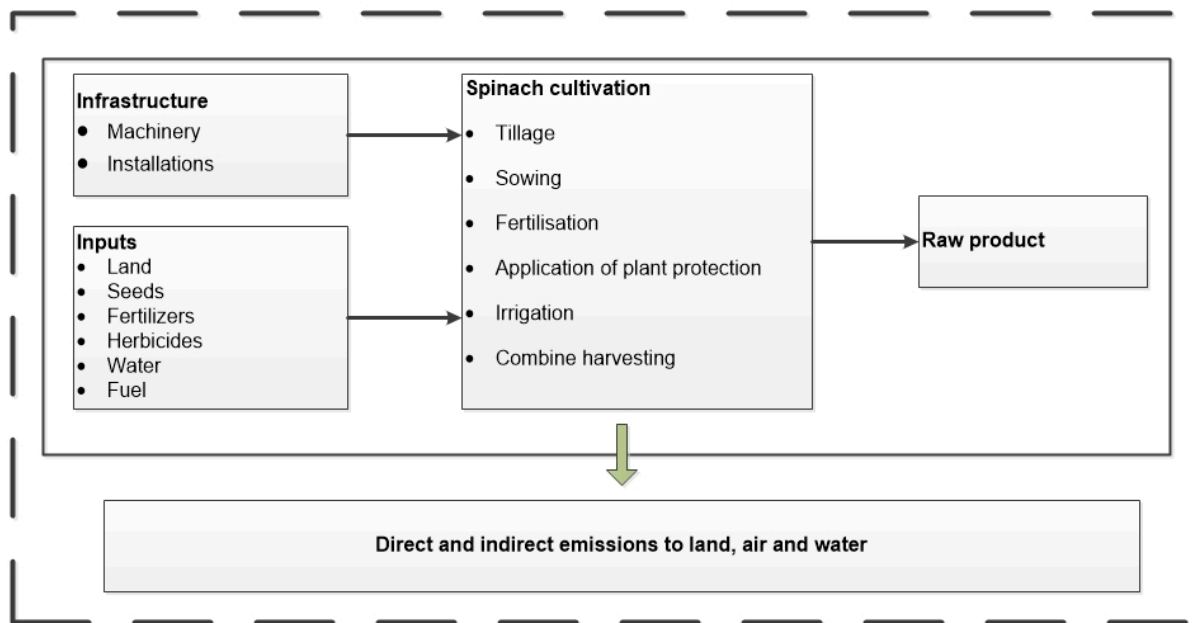


Figure 1. The system boundaries of spinach production considered in this study.

2.1.1. System Description and Data Quality

Data from different spinach producers were obtained from the central and southern regions of Italy under this study. The primary data analyzed in this study came from an agricultural joint-stock consortium company involved in growing and selling frozen vegetables. The company operates on domestic and export markets, producing and selling frozen vegetables for the food industry, retail, and catering customers together with organic vegetables. The company contributes about 5% of the total national spinach production in Italy. The company produces over 6500 tonnes of leaf products such as spinach, chicory, and chard annually. Over 80 local spinach producers registered as members of the joint-stock consortium from different regions, namely; Emilia-Romagna, Marche, Lazio, Umbria, Puglia, Molise, and Basilicata, as shown in Figure 2. In Emilia-Romagna farms are located in Ravenna, for Marche in Macerata, Fermo and Ancona, for Lazio in Latina, for Puglia in Foggia, for Molise in Campobasso, for Umbria in Foligno and Spoleto and for Basilicata in Potenza.

The cultivation of spinach was carried out on open fields using standardized conventional agricultural practices. There were two sowing periods for the spinach reported by the producers. The first sowing period was between November and February and harvested between January and April, while the second sowing period was between July and September and was also harvested between October and December. The farm size for spinach cultivation ranged from 1 ha to 27 ha, with an average of 6.43 ha. The general climatic condition for the central part of Italy is a humid subtropical climate (Köppen–Geiger classification: Cfa) characterized by hot and humid summers and cold to mild winters, while the southern parts have a cold semi-arid climate (Köppen–Geiger classification: BSk).

Due to the open field production system used, the crops are influenced by external weather conditions and more susceptible to pest and disease attacks. Thus, proper soil management is often carried out to break any chain of disease or pest build-up and the over depletion of specific soil nutrients. To this end, producers practice a system of crop rotation where they sequentially cultivate three different crop types: mainly cereals, vegetables, and legumes, before the cultivation of spinach to improve soil quality and to optimize nutrients in the soil. Rotating individual fields away from crops within the same family is critical and can help minimize crop-specific disease and non-mobile insect pests that persist in the soil, overwinter in the field, or field borders. From the data obtained, producers often cultivated wheat before spinach cultivation. Sometimes wheat is substituted with maize or

barley or a horticultural crop such as tomato, peas, endive, turnip, and chicory. Legumes such as fava bean and common bean are cultivated as the penultimate crop and mostly wheat or other less grown canola, sunflower, or alfalfa as the initial crop.

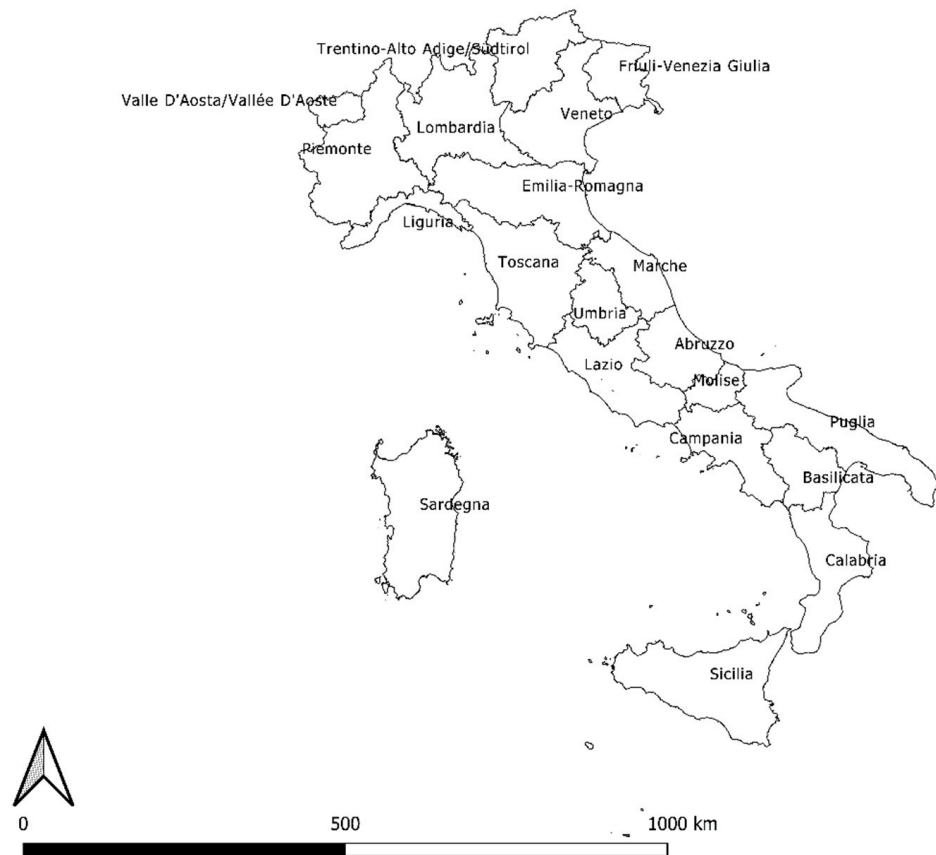


Figure 2. Regional map of Italy.

There are over 50 varieties of spinach, out of which the major ones cultivated by farmers in this study were Crow, Tahiti, Bufflehead, Falcon, Night hawk, Kangaroo, Zanzibar, Gnu, Savrun, Eland, Sparrow, Meerkat, SV 3749, RS 1549 and RS 3549. Varieties are often selected based on their horticultural characteristics, suitability for specific geographical locations, tolerance to weather conditions, and resistance to pest and disease attacks. Based on data gathered from the producers, the yield of spinach per hectare varied significantly, with an average of 9886 kg/ha and a standard deviation of 6706. The high variability could be due to the nature of the soil as spinach grows on different soil types such as clay soil to medium sandy soil characteristic of central to southern Italy. In addition, other factors such as the variety used per producer and the different climatic conditions could have influenced the yield per the location for spinach cultivated under an open system. Land preparation activities before planting selected varieties mainly involved tillage operations include ploughing and harrowing, which are carried out before sowing. Spinach seeds require a finely manicured, firm, level seedbed. The preparation of seedbeds involved disk ploughing followed by rolling with the appropriate spacing.

Two different cultivation systems: organic farming and integrated farming, were used by the producers. The main differences being the type of fertilizers, pesticides and herbicides applied before and during cultivation.

2.1.2. Insecticide and Pesticide Application

In the integrated farming system, the different chemical insecticides and a bioinsecticide used by the producers to control mainly Lepidopteran larvae and aphids are reported

in Table 1. Fungicides used for the control of mildew and botrytis are also reported in the same table. Fungicides are applied when mould growth reaches threshold levels.

Table 1. Insecticide and Fungicide used in integrated farming of spinach.

Insecticide (Active Ingredient)	Target
Ethofenprox	Aphids and bugs
Indoxacarb	Lepidopteran larvae
Chlorantraniliprole	Butterflies and moth
<i>Bacillus Thuringensis</i> (bioinsecticide)	Lepidopteran larvae
Iron phosphate	Slugs
Fungicide (active ingredient)	
Cymoxanil (Pure or with copper)	Mildew
Dimetomorph + Pyraclostrobin	Mildew
Boscalid + Pyraclostrobin	Mildew and Botrytis
Propamocarb	Mildew
Boscalid	Powdery mildew

For the organic spinach cultivation, copper and sulphur derivatives were used as fungicides to control diseases such as powdery mildew, mildew as reported in Table 2, and others such as anthracnose, damping-off, leafy spot, and white rust. Spinosad is a broad-spectrum biological insecticide originating from the fermentation process of a microorganism (*Saccharopolyspora spinosa*) used to control Lepidopteran larvae.

Table 2. Insecticide and Fungicide used for organic farming of spinach.

Insecticide	Target
Spinosad	Lepidopteran larvae
Fungicide	
Copper oxychloride	Mildew
Sulphur	Powdery mildew

2.1.3. Herbicide Application

Herbicides are applied to control weed growth, as they compete with spinach for limited resources and can significantly decrease yield. Under the integrated farming system, different chemicals including S-metolachlor, Metamitron, Lenacil, Phenmedipham, Quisqualop-p-ethyl, Propaquizafop, and Cycloxydim, were applied in appropriate quantities before sowing and after emergence to control the growth of weed. No herbicide under the organic farming system was used but rather a plethora of cultural weed control methods such as crop competition coupled with variety selection, sanitation, crop rotation, and tillage.

2.1.4. Fertilization

From the information provided by the producers, fertilization application for integrated farming occurs in two phases. The first application occurs before sowing, where compost is initially broadcasted on the soil, and two days before sowing bisulphate is applied. The second fertilization occurs after emergence where digestate (product of anaerobic digestion), ammonium sulphate, urea, calcium phosphate, nitric and ammonium compounds are applied. However, no fertilizers are applied for organic spinach cultivation as the crop rotation system used helps improve soil quality coupled with the use of the residual fertilizers from the penultimate cultivation.

2.1.5. Irrigation

Spinach is irrigated during cultivation as the crop needs about 25 to 38 cubic meters per hectare of rain or irrigation per week. However, due to intermittent rainfall patterns,

artificial irrigation is carried out to supplement rainwater. Irrigation was done in three different periods, where in the first period thirty (30) cubic meters of water is applied per hectare immediately after planting. In the second and third periods, twenty (20) cubic meters of water each is applied just before emergence and after emergence. The producers used the sprinkler and furrow irrigation systems.

Finally, between 2–3 months after sowing and growing under optimum conditions, spinach reaches commercial maturity and is harvested. Harvesting using the combined harvester was carried out, which cuts just above the soil line when leaves are young and tender. Spinach leaves can be harvested beginning when plants have five or six leaves; for higher yields, harvest is delayed until plants have 10 to 12 leaves. The spinach leaves regrow and can be ready for harvest again between 10–14 days, although the yield and quality of the second cutting are more than the first. The average yield for the first cutting was 12,271 kg/ha, while the second cutting was 11,982 kg/ha for harvest spinach.

2.2. Life Cycle Inventory (LCI)

The life cycle inventory (LCI) table is related to the average data obtained for spinach production from 73 different producers, reported in Table 3. LCI data for the integrated farming system are average values of 70 producers from all regions. Organic farming data is the average of the three producers in the Cerginola, Puglia region.

Table 3. Life cycle inventory table for spinach cultivation under the integrated and organic farming system (all data are expressed per the FU of 1 kg harvested spinach leaf).

Process/Material.	Unit	Value (Integrated Cultivation)	Value (Organic Cultivation)
Land surface	ha	2.60×10^{-4}	2.54×10^{-4}
Water for irrigation	m ³	2.24×10^{-3}	1.19×10^{-4}
Water for fertilizer/treatment	L	1.38	7.83×10^{-1}
Quantity of seed/sowing material	kg	3.89×10^{-3}	3.81×10^{-3}
Operations			
Sowing	ha	2.60×10^{-4}	2.54×10^{-4}
Rolling	ha	2.60×10^{-4}	2.54×10^{-4}
Ploughing	ha	2.60×10^{-4}	2.54×10^{-4}
Rotary harrow	ha	9.91×10^{-5}	2.54×10^{-4}
Harrowing	ha	1.38×10^{-4}	2.54×10^{-4}
Weeding	ha	1.31×10^{-4}	
Milling	ha	8.07×10^{-6}	
Fertilization	ha	6.37×10^{-4}	
Phytosanitary defence	ha	9.81×10^{-4}	1.36×10^{-3}
Harvesting	ha	1.27×10^{-4}	2.54×10^{-4}
Vertical cutter	ha	1.49×10^{-4}	
Fertilizer			
Ammonium sulphate (27)	kg	7.06×10^{-4}	
Calcium nitrate + Copper (26.5 Cu)	kg	1.32×10^{-5}	
Bio stimulants	L	7.88×10^{-4}	
Ammonium nitrate (34)	kg	2.58×10^{-4}	
Ammonium nitrate (27)	kg	2.42×10^{-4}	
Entec (26)	kg	4.84×10^{-4}	
Simple superphosphate (0:19)	kg	6.78×10^{-4}	
NPK and YaraMila Bulstar (12:12:17)	kg	3.47×10^{-3}	
Digestate (Organic)	kg	5.17×10^{-1}	
Golden Fertil Premium (10:10:15)	kg	1.36×10^{-3}	
Gran NPK (11:22:16)	kg	3.23×10^{-4}	
Entec (25:15)	kg	9.69×10^{-4}	
Monoammonium phosphate (12:52)	kg	3.23×10^{-4}	
Diammonium phosphate (18:46)	kg	3.57×10^{-2}	

Table 3. Cont.

Process/Material.	Unit	Value (Integrated Cultivation)	Value (Organic Cultivation)
Urea/Entec (46)	kg	3.61×10^{-2}	
Calcium nitrate	kg	1.90×10^{-2}	
Herbicide			
S-metolachlor	kg	4.45×10^{-5}	
Metamitron	kg	4.06×10^{-4}	
Lenacil	kg	1.09×10^{-4}	
Phenmedipham	kg	3.44×10^{-5}	
Quizalofop-p-ethyl	kg	2.23×10^{-5}	
Propaquizafop	kg	6.44×10^{-5}	
Cycloxydim	kg	1.29×10^{-5}	
Insecticide			
Ethofenprox	kg	5.08×10^{-5}	
Indoxacarb	kg	2.35×10^{-6}	
Chlorantraniliprole	kg	1.81×10^{-5}	
Iron phosphate	kg	6.61×10^{-4}	
Spinosad	L		3.75×10^{-4}
Fungicide			
Cymoxanil (Pure)	kg	5.10×10^{-5}	
Cymoxanil (with Cu)	kg	5.22×10^{-5}	
Dimetomorph + Pyraclostrobin	kg	5.18×10^{-5}	
Propamocarb	kg	1.53×10^{-5}	
Boscalid	kg	2.30×10^{-5}	
Copper oxychloride	kg		3.83×10^{-4}
Sulphur	kg		1.28×10^{-3}

2.3. Calculations, Allocations, and Emission Models

In the present study, all flows and related impacts were associated with the product under analysis. As there are no by-products and co-products, no allocation procedure was therefore taken into consideration. The data for the different farms were categorized based on the geographical location of the farm and the type of farming system (organic vs. integrated). Primary data was for reference years 2019 and 2020 obtained from 73 out of which on a regional basis 42 were from Marche, 24 from Puglia, three from Umbria, and one from Emilia-Romagna, Lazio, Molise, and Basilicata. Out of the 73 farms data analyzed, three cultivated organic spinach in Cerignola, Province of Foggia (Puglia region), while the others used the integrated production system. With regards to emissions from the application of pesticides, the fraction of the active ingredient entering the soil was estimated to be 85% of the total applied quantity, 10% for air, and 5% for water [34]. Due to the unavailability of region-specific data, calculation on emissions for fertilizer application relied on information from the Product Category Rules (PCR) for arable and vegetable crops [35]. Emission factors for air included: the NH_3 and NO emissions [5], N_2O -direct and indirect emissions [36], emission factors for water: nitrates (IPCC, 2019), urea fertilization, liming, and phosphorus [36]. The background life cycle inventory data came from Eco-invent v.3.01.

2.4. Life Cycle Impact Assessment

The collected and aggregated data were input in the SimaPro 8.2.3 software with updated databases include Eco-invent (v.3.01) and Agri-footprint (v. 2.0), obsolete databases, or information related to countries technologically or geographically too far from Italy have not been considered. This helped in the construction of the process flows to model the production systems. The CML_IA baseline V3.01 method [37] was applied to estimate the environmental impacts based on the midpoint approach for 1 kg harvested spinach leaf. The impact categories examined under this method are in Table 4.

Table 4. Mid-point impact categories and their description for the CML_IA baseline method.

Impact Category	Acronym	Description
Abiotic Depletion Potential (elements) [38] Abiotic Depletion Potential (fossil fuel) [38]	ADP (E) ADP (FF)	Abiotic depletion is concerned with the protection of human welfare, human health, and ecosystem health. This impact category indicator is related to the consumption of non-biological resources such as minerals and fossil fuels on a global scale as it measures the scarcity of a substance over time [39,40].
Global Warming Potential 100 yr [41]	GWP	The noticeable change in global temperatures due to the emission of greenhouse gases (GHGs) mainly through anthropogenic activities has become a critical environmental concern necessitating in-depth investigations [39,40]. GWP is a method for comparing the climate effects of emissions of different GHGs like CO ₂ , CH ₄ , and N ₂ O [42].
Stratospheric Ozone Layer Depletion Potential [43]	ODP	Depleting the ozone layer due to anthropogenic emissions of ozone-depleting substances such as CFCs, halogens, and HCFCs causes a larger fraction of UV-B radiation to reach the earth's surface. This radiation can have harmful effects on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles, and materials [39,40].
Human Toxicity Potential [44]	HTP	HTP is concerned with the toxic effects of chemical substances on humans. It is a calculated index that reflects the potential harm of a unit of chemical released into the environment. It also depends on both the inherent toxicity of a compound and its potential dose. These harmful chemicals such as Arsenic, Na ₂ Cr ₂ O ₇ , and HF can have a carcinogenic effect in humans when emitted into air or water [39,40,45].
Ecotoxicity - Fresh Water Aquatic Ecotoxicity Potential - Marine Aquatic Ecotoxicity Potential - Terrestrial Ecotoxicity Potential	FAETP MAETP TETP	Environmental toxicity is measured as three separate impact categories: freshwater ecotoxicity, marine ecotoxicity, and terrestrial ecotoxicity, which examine the impact on freshwater, marine, and land, respectively. Ecotoxicity is due to emissions of toxic substances such as heavy metals to air, water, and soil. Ecotoxicity potentials are calculated with the USES-LCA, which is a multi-media fate, exposure, and effects model [39,40,46].
Photochemical Ozone Creation Potential [47,48]	POCP	Photochemical ozone is formed by the reaction of volatile organic compounds and NO _x in the presence of heat and sunlight and is harmful to human health and ecosystems and may potentially damage crops. The impact category depends largely on the amounts of CO, SO ₂ , NO, NH ₄ , and NMVOC (non-methane volatile organic compounds) [39,40].
Acidification Potential [49]	AP	Some emissions from anthropogenic activities can reduce pH due to the acidifying effects in water and soil systems. Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems, and materials consequently, decreasing biodiversity and damaging the quality of ecosystems. Gases with high acidifying potential include NH ₃ , nitrogen oxides (NO _x), and Sulphur oxides (SO _x) [39,40].
Eutrophication Potential [49]	EP	Eutrophication includes all impacts due to the accumulation of macro-nutrients in the ecosystem caused by emissions of nutrients such as NH ₃ , [NO ₃] ⁻ , NO _x , and P to air, water, and soil, which could result in abnormal productivity [39,40].

The means and standard deviations of the impact scores were obtained for different locations (central Italy and southern Italy) and farming systems (integrated farming and organic farming). An independent sample *t*-test was also conducted at a confidence level of 95% ($p < 0.05$) to indicate if there were significant differences among the tested locations and farming systems using the SPSS Statistics V21.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Impact Scores for Regions

The average impact scores for spinach produced under the integrated farming system for different categories were calculated for two cluster locations: central Italy and southern Italy. Regions within Central were Marche, Emilia-Romagna, Lazio, and Umbria, while Southern regions were Molise, Puglia, and Basilicata. The average impact scores and the corresponding standard deviations are in Table 5. Generally, central Italy recorded higher values than southern Italy across all the impact categories. Due to the high variability among the data obtained from the different producers, high standard deviations were consequently obtained for all impact scores.

Table 5. Average impact scores for 1 kg freshly harvested spinach in central and southern Italy.

Impact Category	Central (Average)	Central (Std. Dev.)	Southern (Average)	Southern (Std. Dev.)
ADP (E) (kg Sb eq.)	5.19×10^{-6}	5.47×10^{-6}	4.28×10^{-6}	3.59×10^{-6}
ADP (FF) (MJ)	10.80	58.56	10.21	58.56
GWP (kg CO ₂ eq.)	0.56	0.61	0.47	0.43
ODP (kg CFC-11 eq.)	3.40×10^{-8}	3.96×10^{-8}	2.75×10^{-8}	2.64×10^{-8}
HTP (kg 1,4-DB eq.)	9.27×10^{-2}	1.01×10^{-1}	7.68×10^{-2}	6.87×10^{-2}
FAETP (kg 1,4-DB eq.)	5.87×10^{-2}	6.23×10^{-2}	4.98×10^{-2}	4.68×10^{-2}
MAETP (kg 1,4-DB eq.)	184.26	203.53	156.90	161.38
TETP (kg 1,4-DB eq.)	2.92×10^{-3}	3.97×10^{-3}	2.54×10^{-3}	3.53×10^{-3}
POCP (kg C ₂ H ₄ eq.)	9.06×10^{-5}	9.66×10^{-5}	7.59×10^{-5}	6.77×10^{-5}
AP (kg SO ₂ eq.)	1.04×10^{-2}	1.01×10^{-2}	8.95×10^{-3}	7.80×10^{-3}
EP (kg PO ₄ ³⁻ eq.)	5.46×10^{-3}	5.86×10^{-3}	4.61×10^{-3}	4.18×10^{-3}

A QGIS map was created to visualize of the geospatial data and the relative distances of the farm locations to the company can also be visualized in Figure 3.

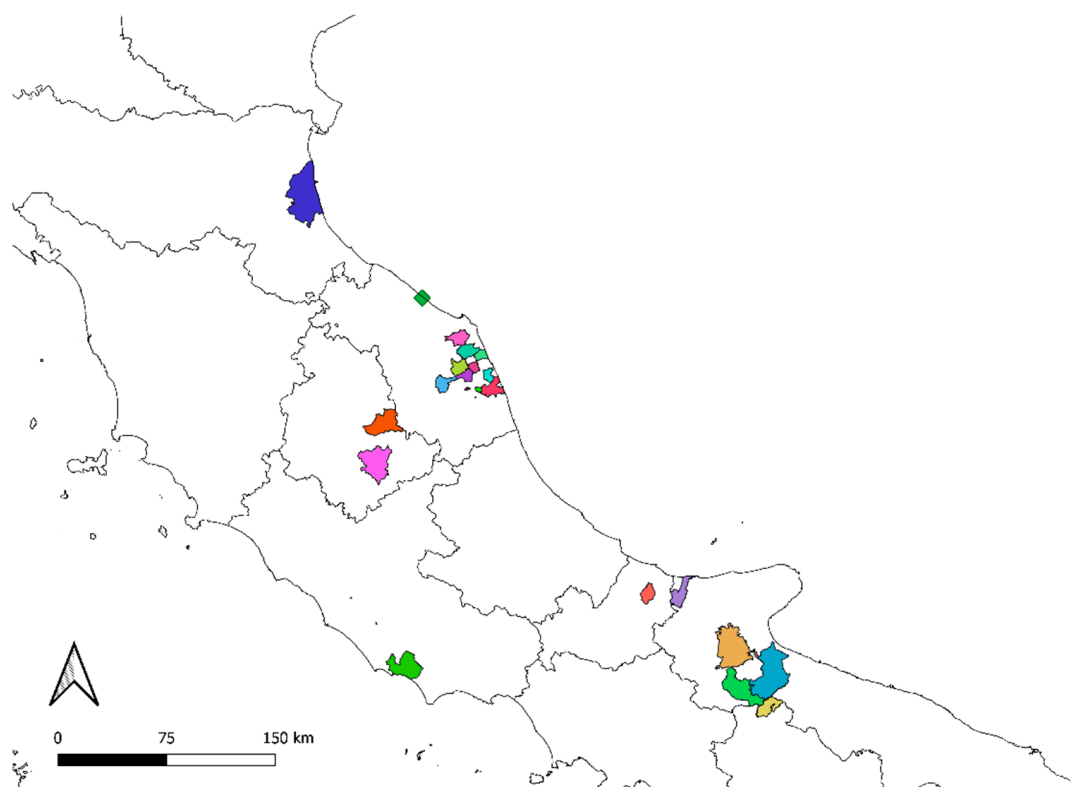


Figure 3. The geographical locations of the farms (coloured polygons) relative to the mother company (green rhombus).

3.2. Impact Scores for Different Farming Systems

Three producers in Cerignola town, Province of Foggia in the Puglia region, engaged in organic spinach cultivation. Within Cerignola, five other producers used the integrated spinach farming system. The average impact scores for the different categories per 1 kg of harvested spinach for the different farming systems are in Table 6. A relative comparison of the two farming systems is in Figure 4. From the results obtained, the impact scores for integrated farming were higher than those obtained for organic spinach cultivation for all impact categories except for ADP (elements) and ODP.

Table 6. Impact results for the different spinach cultivation systems per FU in Cerignola (Puglia region).

Impact Category	Unit	Organic Farming	Integrated Farming
ADP (elements)	kg Sb eq.	2.11×10^{-6}	1.80×10^{-6}
ADP (fossil fuels)	MJ	1.02	1.79
GWP (100 yr)	kg CO ₂ eq.	0.075	0.20
ODP (steady state)	kg CFC-11 eq.	2.20×10^{-8}	1.02×10^{-8}
HTP (inf.)	kg 1,4-DB eq.	3.58×10^{-2}	3.97×10^{-2}
FAETP (inf.)	kg 1,4-DB eq.	1.37×10^{-2}	2.91×10^{-2}
MAETP (inf.)	kg 1,4-DB eq.	49.10	81.36
TETP (inf.)	kg 1,4-DB eq.	2.91×10^{-5}	2.13×10^{-3}
POCP	kg C ₂ H ₄ eq.	2.71×10^{-5}	4.31×10^{-5}
AP	kg SO ₂ eq.	6.35×10^{-4}	3.26×10^{-3}
EP	kg PO ₄ ³⁻ eq.	1.79×10^{-4}	1.48×10^{-3}

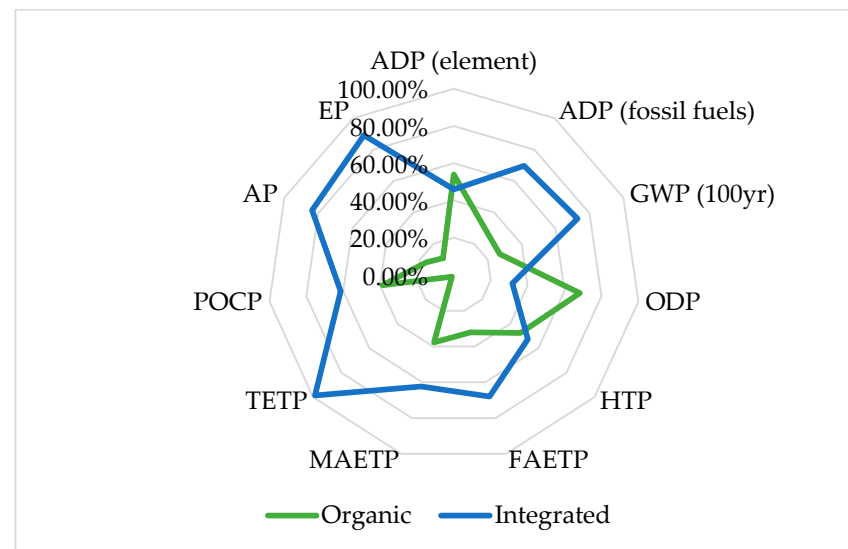


Figure 4. Relative impact of organic farming (green line) and integrated farming (blue line), system boundary considered: from cradle-to-farm gate for spinach cultivation in Cerignola (Puglia region).

3.3. Contribution Analysis

The relative impact of materials and operations for both the organic and integrated cultivation systems in reference to the FU are shown in Figures 5 and 6, respectively. Different processes and materials had varying degrees of impact on the various impact categories. However, for organic spinach cultivation, sowing, tillage, and pesticide predominantly had the highest shares across the impact categories except for ODP, where irrigation reported the highest contribution. On the other hand, the contribution analysis on integrated farming showed that direct emissions from fertilizer use recorded the highest shares for EP, AP, and GWP. Other significantly impacting materials and processes included: indirect emissions from fertilizers, pesticides, tillage, and sowing material.

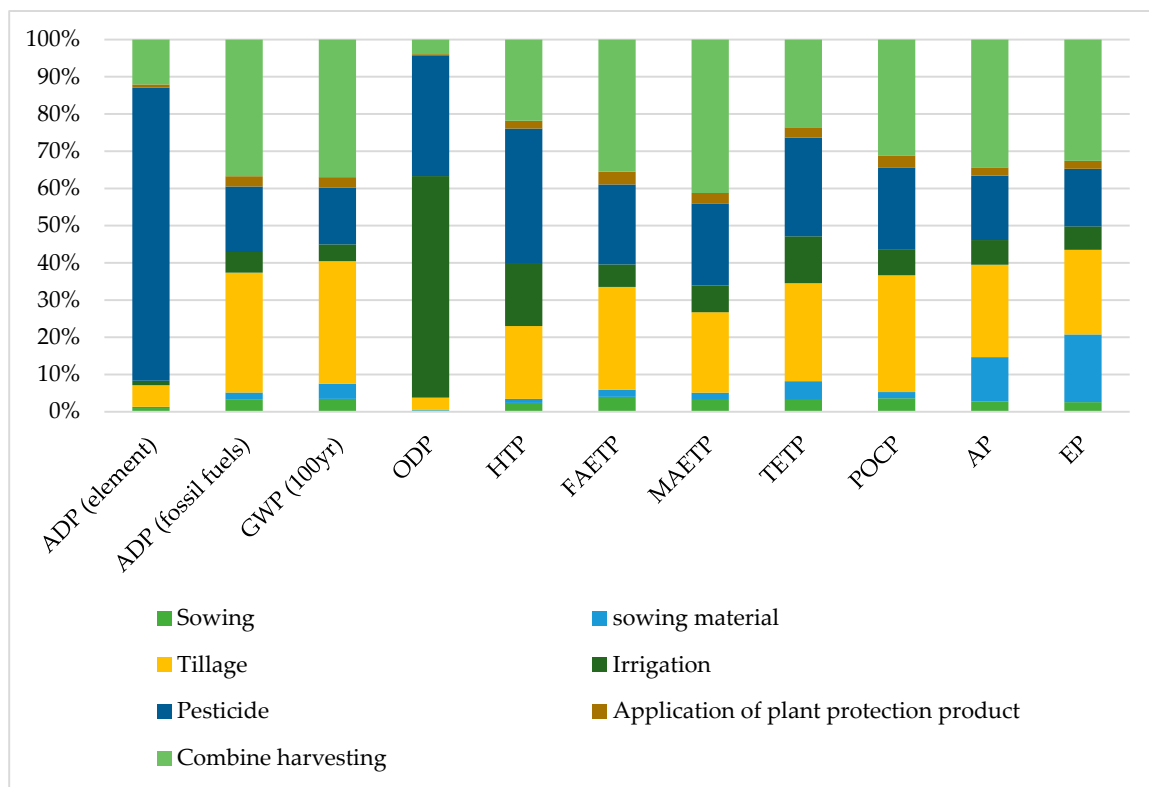


Figure 5. Impact share of input-output for organic farming.

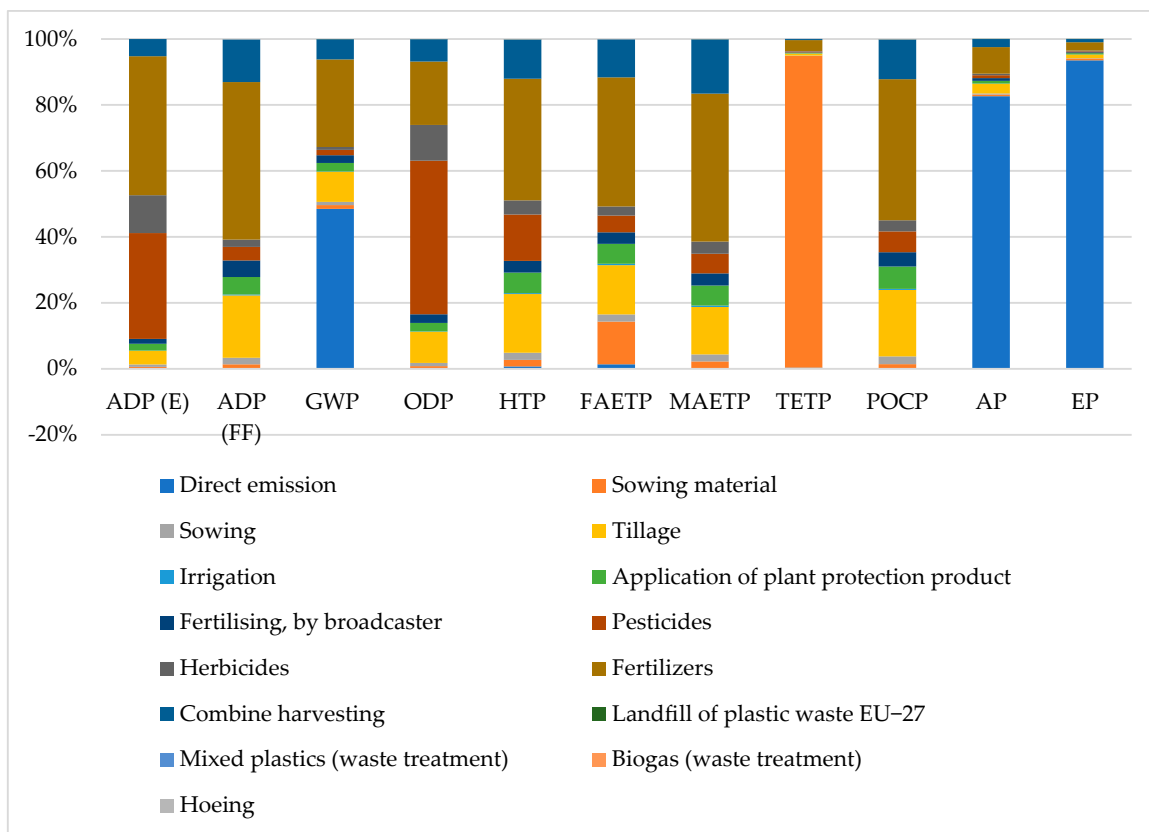


Figure 6. Impact share of input-output for integrated farming.

4. Discussion

4.1. Depletion of Abiotic Resources (ADP)

The results obtained on clustered regional basis showed that ADP mean scores were higher in central Italy than southern Italy for both elements and fossil fuels. For ADP (E), central Italy scored 5.19×10^{-6} kg Sb eq., while southern Italy scored 4.28×10^{-6} kg Sb eq./FU as indicated in Table 5. The same was true for ADP (FF), where central and south Italy had scores of 10.80 MJ/FU and 10.21 MJ/FU, respectively. Wide variations in ADP (E) and ADP (FF) scores for producers in both regions are reported in Table 5. There was no statistically significant difference for ADP (E) ($p = 0.468$) and ADP (FF) ($p = 0.310$).

In Cerignola, organic spinach reported a higher ADP (E) score of 2.11×10^{-6} kg Sb eq. and a lower ADP (FF) score of 1.02 MJ as compared to ADP scores of 1.80×10^{-6} kg Sb eq. and 1.79 MJ/FU for integrated farming, respectively. There was no statistically significant difference ($p = 0.850$ and 0.569) between the farming systems for ADP (E) and (FF), respectively. The main inputs accounting for the differences were inorganic fertilizer and chemical pesticides due to emissions related to their production. For ADP (E), spinach produced through the organic farming system revealed that pesticides and combined harvesting contributed the highest impact shares of 84% and 13%, respectively. High pesticide contribution could be due to elements/minerals such as sulfur, copper, oxygen, and chlorine needed for fungicides production. For ADP (FF), combine harvesting (37.98%), tillage (33.35%), and pesticides (18.22%) were the main impact contributors due to the extraction and use of fossil fuel in the manufacturing and operation associated with these materials and processes. In contrast, spinach produced under the integrated system revealed that for ADP (E), fertilizer and pesticides were the most impacting materials contributing shares of 42.15% and 32.08%, respectively. Fertilizer (47.83%) and tillage (18.91%) were also the most impacting materials for ADP (FF).

4.2. Global Warming (GWP)

The GWP results for time horizon of a 100 years based on the characterization model developed by the IPCC on a global scale obtained for the clustered locations are in Table 5. Results show that central Italy had a relatively higher mean score of 0.56 kg CO₂ eq. compared to southern Italy's 0.47 kg CO₂ eq./kg of fresh spinach. There was high variability in impact scores among the producers. High standard deviations of 0.61 kg CO₂ eq./kg and 0.43 kg CO₂ eq./kg were obtained for central and southern Italy, respectively. However, no statistically significant difference was observed ($p = 0.592$). Eight individual producers in Marche and Puglia were recorded over 1.00 kg CO₂ eq./FU with the highest score being 3.46 kg CO₂ eq./FU while five producers in the same regions had less than 0.05 kg CO₂ eq./FU.

The GWP results based on the cultivation system revealed that integrated farming had a higher impact score of 0.20 kg CO₂ eq. than 0.075 kg CO₂ eq./FU for organic farming in Cerignola. However, no statistically significant difference was observed ($p = 0.394$). The main reason for the difference in impact scores is the direct emission of N₂O greenhouse gas (GHGs) from the use of inorganic fertilizer in the integrated farming system. Seo et al. [29], reported GWP values of 0.49 kgCO₂ eq./kg for integrated system and 0.29 kgCO₂/kg spinach for eCO₂ system which are higher values obtained in this present study. Theurl et al. [50] also reported similar range values of 0.094 and 0.115 kg CO₂ eq./kg fresh organic spinach under a polytunnel cultivation system, which is consistent with values obtained in this study. Frankowska et al. [30] also reported an estimated GWP score of 0.17 kg CO₂ eq./kg spinach for the cultivation phase of spinach in England. However, Shiina et al. [28] reported a significantly higher GWP value of 2.3 kg CO₂ eq./kg of spinach produced in Japan. Differences could be due to the greenhouse system of cultivation used in the study, the smaller size of the 760 m² hybrid type plant factory under consideration, and the inclusion of packaging within the system boundary. Under the organic farming system, combine harvesting, tillage, and pesticides contributed the highest impact shares of approximately 38.32%, 34.12%, and 15.74%, respectively, due to GHG emissions associated with the manufacturing, synthesis, and operations of these materials and processes.

Concerning impact share from the various materials and processes integrated spinach production, direct N₂O gas emitted into the air from inorganic nitrogen-based fertilizers contributed 48.49% to the total share. Indirect emissions from the synthesis and use of fertilizers also contributed 26.57% to the total impact share for GWP.

4.3. Stratospheric Ozone Layer Depletion (ODP)

The average ODP impact scores of ODP results for central and southern Italy were 3.40×10^{-8} kg CFC-11 eq. and 2.75×10^{-8} kg CFC-11 eq./FU, respectively. Results show that central Italy had a relatively higher mean score, although with high variability in impact scores among the producers. No statistically significant difference was observed ($p = 0.932$) between central and southern Italy. The most impacting input for central and south Italy was pesticide, accounting for 45–50% of the total impact score. Urea from fertilizer also contributed about 20%. Nitrogen present in urea has the potential to form NOX that can catalytically deplete stratospheric ozone. The depletion occurs via the nitrogen cascade when reactive nitrogen moves through various environmental systems particularly, the atmosphere and terrestrial ecosystems. The direct effect of reactive nitrogen from the breakdown of urea has the potential to cause ozone-induced injury to crops and natural ecosystems and increases predisposition to be attacked by pathogens and insects [51,52].

Concerning the type of cultivation system, organic farming had a higher score of 2.20×10^{-8} kg CFC-11 eq., compared to 1.02×10^{-8} kg CFC-11 eq./FU for integrated farming, as shown in Table 6. The difference was due to the relatively higher amount of organic pesticide used. No statistically significant difference was observed ($p = 0.654$) between organic and integrated farming in Cerginola, Puglia region. Frankowska et al. [30] reported an ODP value of 5×10^{-10} kg CFC-11 eq./kg for the spinach supply chain in the UK. Impact share of materials and processes for organic farming showed that emissions associated with irrigation and pesticide alone accounted for 59.72% and 32.59%, respectively, of the total share as presented in Figure 5. On the other hand, emissions associated with the synthesis of pesticide, fertilizer, and herbicide contributed 47.52%, 20.94%, and 11.29% to the overall impact score obtained for ODP under the integrated farming system displayed in Figure 6.

4.4. Human Toxicity (HTP)

The average scores for HTP reported in Table 5 shows central Italy had a higher score than southern Italy, 9.72×10^{-2} kg 1,4-DB eq. and 7.68×10^{-2} kg 1,4-DB eq./FU, respectively. There was a wide variation in impact scores obtained for the producers in central and southern Italy, as reported in Table 5. However, there was no statistically significant difference ($p = 0.695$) between the two cluster locations. Urea was the most impacting substance as the consumption of diets having high nitrate contents has contributed to endogenous nitrosation, which could lead to a thyroid condition, various kinds of human cancers, neural tube defects (during foetus development), and diabetes [53].

The HTP value for integrated farming obtained in Cerginola was 3.97×10^{-2} kg 1,4-DB eq., similar to 3.58×10^{-2} kg 1,4-DB eq./FU for organic spinach. There was no statistically significant difference ($p = 0.96$) between the two farming systems. Frankowska et al. [30] also reported an estimated similar human toxicity value of 6×10^{-2} kg 1,4-DB eq./kg spinach produced in the UK. The percentage contribution of materials and processes to the total impact share for organic farming shows, pesticide, combine harvesting, and tillage recorded the highest shares of 36.12%, 21.82%, and 19.58%, respectively. Most impacting materials and processes for integrated farming were also fertilizer, tillage, and pesticide contributing, 36.89%, 17.78%, and 14.07%, respectively.

4.5. Ecotoxicity (MAETP, FAETP, TETP)

On the clustered regional level, central Italy had higher values for MAETP, FAETP, and TETP than southern Italy, as reported in Table 5. Average scores of 5.87×10^{-2} kg

1,4-DB eq./kg, 184.26 kg 1,4-DB eq./kg and 2.92×10^{-3} kg 1,4-DB eq./kg were obtained for FAETP, MAETP, and TETP, respectively in central Italy while 4.98×10^{-2} kg 1,4-DB eq./kg, 156.90 kg 1,4-DB eq./kg and 2.54×10^{-3} kg 1,4-DB eq./kg for south Italy. There was high variability in the impacts from producers in the different regions reported in Table 5. However, there was no statistically significant difference between central and south Italy for all three ecotoxicity impact categories.

Spinach produced under integrated farming in Cerignola recorded higher values for FAETP, MAETP, and TETP compared to scores for organic farming reported in Table 6. Values of 1.37×10^{-2} kg 1,4-DB eq./kg, 49.10 kg 1,4-DB eq./kg and 2.91×10^{-5} kg 1,4-DB eq./kg were obtained for FAETP, MAETP, and TETP respectively under organic spinach cultivation while 2.91×10^{-2} kg 1,4-DB eq./kg, 81.36 kg 1,4-DB eq./kg and 2.13×10^{-3} kg 1,4-DB eq./kg for integrated farming. However, there was no statistically significant difference between ecotoxicity impact scores for organic and integrated farming under FAETP, MAETP, and TETP. Frankowska et al. [30] reported FAETP and MAETP values of 4.1×10^{-3} kg 1,4-DB eq./kg and 3.6×10^{-3} kg 1,4-DB eq./kg for spinach cultivation and 4.2×10^{-3} kg 1,4-DB eq./kg for the supply chain of spinach in the UK.

Regarding impact share for organic spinach production, emissions associated with combined harvesting, tillage, and the synthesis of pesticides contributed the most, shown in Figure 5. Combine harvesting contributed 35.52%, 41.23% and 23.57% to FAETP, MAETP and TETP respectively. Tillage also contributed 27.61%, 21.58% and 26.36% to FAETP, MAETP and TETP respectively while pesticide contributed 21.45%, 22.05% and 26.54% in the same order. For integrated farming, different materials and processes contributed significantly to the three separate impact categories, shown in Figure 6. Fertilizer (39.13%), tillage (14.91%), and sowing material (12.95%) were the major contributors to the FAETP score obtained. For MAETP, fertilizer (44.85%) and combine harvesting (16.47%) recorded the highest shares due to emissions associated with the synthesis of inorganic fertilizer and the entire tillage operation. Emissions associated with the production of sowing material resulted in a significant impact share of 94.53% to the total TETP score obtained.

4.6. Photochemical Ozone Creation (POCP)

Central Italy had a relatively higher average EP score of 9.06×10^{-5} kg C₂H₄ eq./FU while southern Italy had 7.59×10^{-5} kg C₂H₄ eq./FU reported in Table 5. There was no statistically significant difference ($p = 0.546$) between POCP scores for central and southern Italy, although there was high variability in impact scores among producers. POCP score was mainly influenced by fertilizer applied.

Integrated farming was more impacting than organic farming in terms of POCP. POCP scores for the organic farming system was 2.71×10^{-5} kg C₂H₄ eq., while integrated farming obtained 4.31×10^{-5} kg C₂H₄ eq./FU as shown in Table 6. There was no statistically significant difference ($p = 0.634$) between the two cultivation systems. In terms of impact share contributions for organic farming, tillage and combine harvesting recorded the highest values of 31.37% and 31.24%, respectively. Emissions from fertilizer use (42.77%) and tillage (20.18%) were most impacting under integrated farming. Urea was the most impacting substance. Reactive nitrogen from urea can form NO_x, which alters a wide array of biogeochemical processes and exchanges among environmental reservoirs. Consequently leading to negative photochemical transformations and greenhouse effects within the atmosphere [50].

4.7. Acidification (AP)

The average scores for AP reported in Table 5 shows central Italy had a higher score than southern Italy, 1.04×10^{-2} kg SO₂ eq. and 8.95×10^{-3} kg SO₂ eq./FU, respectively. There was a wide variation in impact scores obtained for the producers in central and southern Italy, as reported in Table 5. However, there was no statistically significant difference ($p = 0.892$) between the two cluster locations. Nitrogen-based fertilizers were the major contributor to AP. Reactive nitrogen (NO_x) has an acidification effect on ecosystems, especially

on soils and surface waters. The ammonium-N in fertilizers undergo nitrification, which releases hydrogen (H⁺), increasing acidity. As the percentage of ammonium increases in a given fertilizer, the acidifying potential will also be increased, thus reducing pH [50].

Concerning the farming systems in Cerignola, results for the AP in this study revealed that integrated farming had a higher score of 3.26×10^{-3} kg SO₂ eq./FU compared to 6.35×10^{-4} kg SO₂ eq./FU obtained for the organic farming. However, there was no statistically significant difference ($p = 0.405$) between the farming system. The main difference could be attributed to the direct and indirect emission of ammonia and nitrogen oxides from the fertilizer applied in integrated farming. Direct and indirect emissions from fertilizer accounted for 84.77% of the total AP score obtained for integrated farming due to high amounts of different nitrogen-based fertilizers used. For the organic farming system, combine harvesting, tillage, and pesticide were the most impacting materials, and operations accounted for 34.35%, 24.83%, and 17.32% of the total score, respectively.

4.8. Eutrophication (EP)

Central Italy had a higher average EP score of 5.46×10^{-3} kg PO₄³⁻ eq., while southern Italy had 4.61×10^{-3} kg PO₄³⁻ eq./FU reported in Table 5. There was high variability in impact scores obtained for the producers in central and southern Italy. The standard deviations of 5.86×10^{-3} kg PO₄³⁻ eq. and 4.18×10^{-3} kg PO₄³⁻ eq. for central and south Italy, respectively, were reported in Table 5. However, there was no statistically significant difference ($p = 0.896$) between the two cluster locations. Direct emissions of nitrogen and potassium into both air and water from the fertilizers used accounted for about 90% of the total impact EP scores. Ammonium, ammonia, and phosphates from fertilizers can leach into water bodies and facilitate algae growth. As the percentage of N and P increases in a given fertilizer, the eutrophication potential also increases.

There was a wide disparity in EP values obtained for integrated farming and organic farming in Cerignola. The former recorded 1.48×10^{-3} kg PO₄³⁻ eq. and the latter 1.79×10^{-4} kg PO₄³⁻ eq./FU. However, there was no statistically significant difference ($p = 0.408$) between the two cluster locations. The main difference was due to direct and indirect emissions of nitrogen and phosphorus derivatives from the fertilizer applied in integrated farming. Direct and indirect emissions from fertilizer contributed 94.11% to the total EP value obtained for integrated farming due to a large amount of different nitrogen and phosphorus-based fertilizers used. Emissions associated with the production and operation of combine harvesting, tillage, sowing material, and pesticides were the most impacting inputs for organic spinach cultivation, contributing 32.58%, 22.72%, 18.18%, and 15.49%, respectively.

5. Conclusions

Few environmental impact assessment studies have been conducted on real-life spinach production systems. The production systems in central and southern Italy have been analyzed in this study to overcome this limitation. The environmental profiles of spinach cultivated by different producers have been assessed using the life cycle approach. Analysis was to help develop a tentative agricultural eco-design for a top spinach processing company. Data from 73 farms were analyzed in total, 46 in central Italy and 27 in southern Italy. Mean scores on a location basis showed that producers in central Italy recorded slightly higher values across all impact categories than south of Italy. The GWP score for central and southern was 0.56 kg CO₂ eq. and 0.47 kg CO₂ eq. for 1 kg of harvested spinach. There was wide variability in the impact scores for both locations. No statistically significant difference was seen. The results obtained on a geographical location basis in this study were consistent with other studies conducted in Europe and Asia. Fertilizers and pesticides were the main contributors to AP, EP, ODP, HTP, and POCP. Other impacting operations and materials were combine-harvesting, tillage, and pesticides.

Out of 8 farms data analyzed in Cerignola, Province of Foggia (Puglia region), three cultivated organic spinach, while five used the integrated production system. There was

a higher variability in data collected from spinach producers under both the integrated farming system and organic farming system. Impacts associated with integrated farming were higher than those obtained for organic farms for all impact categories except for ODP and ADP(E). No statistically significant difference was seen for all impact categories. However, there were 70 producers involved in integrated farming compared to only three producers involved in organic spinach cultivation. Therefore, more LCA studies should be conducted on organic spinach production and other types of cultivation systems particularly, for protected systems for better comparison and advocacy of more efficient and sustainable spinach cultivation.

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