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Carbon footprint of hemp and sunflower oil in southern Italy: A case study

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A R T I C L E I N F O

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A B S T R A C T

The proteoleaginous plants demand has seen significant growth, leading to an expansion of the sunflower (*Helianthus annuus*, L.) and industrial hemp (*Cannabis sativa*, L.) cultivation area in Italy. However, by-products obtained during seed oil extraction and agricultural residues are often unused due to the absence of a receptive market and nearby processing centers. The carbon footprint (CF) methodology was used to compare the two supply chains considering the soil incorporation of all crop residues and by-products. The boundary of the supply chains analyzed includes all the agricultural processes that occur during cultivation and the subsequent oil extraction phase. Furthermore, research explored the direct and indirect environmental benefits of incorporating by-products into the soil, in terms of reducing the need for mineral fertilizers to restore soil fertility due to the nutrients contained in the buried biomass, and the potential carbon sequestration achievable. Results show that 1 kg of sunflower and hemp oil release 4.49 kg CO_2-eq and 23.34 kg CO_2-eq, respectively. Agriculture represents the most impacting phase and, in particular, fertilization, tillage and harvest are responsible for high emissions. The different results between the two supply chains can be attributed mainly to yield and extraction efficiency. The use of by-products as amended in the soil (avoided fertilizers) contributes to a reduction of greenhouse gas (GHG) emissions by −0.53 kg CO_2-eq and −7.87 kg CO_2-eq per kg of sunflower and hemp oils, respectively. Additionally, the sequestration of carbon in biomass can result in a further reduction of −1.16 and −33.6 kg CO_2-eq per kg of sunflower and hemp oil, respectively. In summary, sunflower oil production emits 74 % less CO_2 than hemp oil. However, if all crop biomass is buried, hemp has the potential to be more sustainable. This phenomenon depends on many factors such as soil type, climate, and farming practices. The study outcomes can aid policymakers, farmers, and the agribusiness to make informed decisions on promoting and expanding sustainable sunflower and hemp cultivation in Italy.

1. Introduction

According to the United Nations World Population Prospects 2022, the world population will increase by 2 billion people over the next 30 years, from 7.7 billion today to 9.7 billion in 2050 (United Nations Department of Economic and Social Affairs Population Division, 2022). This means that a significant increase in food, feed, and fiber production will be required in the coming years to meet the needs of the growing population. Adopting intensified cropping systems could be a viable way to increase food production, although these practices require high agricultural inputs such as inorganic fertilizers, pesticides, and fuel. Although they enable high crop yields, they are considered hazardous because they emit greenhouse gasses (GHGs) and have environmental consequences (Blandford and Hassapoyannes, 2018; Palmieri et al., 2017a). Similarly, the management of uncultivated land negatively affects carbon stocks in natural vegetation and soil, leading to a rapid loss of the planet's carbon stocks, which in turn reduces biodiversity and environmental impacts (Dale, 1997). Farmers are challenged to develop

Abbreviations: AGB, above ground biomass; C, carbon; CAP, common agricultural policy; CDM, clean development mechanism; CEL, cellulose; CF, carbon footprint; CO, carbon monoxide; FU, functional unit; GHG, greenhouse gases; GWP, global warming potential; HC, hydrocarbons; HEM, hemicellulose; K2O, potash; LIG, lignin; N, nitrogen; NDC, nationally determined contribution; NDF, neutral detergent fraction; NOx, nitrogen oxides; P2O5, phosphate; PM, particulate matter; SOC, soil organic carbon; VCM, voluntary carbon market.

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effective agricultural practices to reduce GHGs emissions so that they can strategically reduce the carbon footprint (CF) of products grown on the farm. There are several strategies to reduce the CF of crops, generally associated with high technical efficiency, above average yields, and better profit margins. Another option is to develop innovative food products from alternative crops.

The renewed interest in proteoleaginous crops in Italy, especially sunflower (*Helianthus annuus,* L.), has led to an increase in the cultivation area in the central and northern parts of the country, providing an alternative to maize and wheat.

The production of sunflower oil and seeds in Italy is significantly below the demand of the domestic market, which is currently met by imports, mainly from Eastern European countries (Ukraine, Romania, Hungary, and Bulgaria). Italian sunflower acreage has fluctuated between 100 and 122 thousand hectares in the last decade (ISTAT, 2020), but at least 600 thousand hectares would be necessary to meet food industry demand, especially for high oleic sunflower seeds, which are most in demand by the food industry. Thus, the area cultivated could be expanded, even considering the demand, which continues to increase, although in fluctuating phases.

Industrial hemp (*Cannabis sativa*, L.) is one of the oldest crops grown by farmers, and in recent years it has attracted renewed interest in the agricultural sector due to the multitude of uses of its products. Indeed, this crop has always been cultivated for fiber production, while lately hemp flowers and seeds have been used mainly in the pharmaceutical and food industries. Hemp oil is known for nutritional and health benefits due to high content of polyunsaturated fatty acids (omega-3 and omega-6) and other bioactive minor components (Liang et al., 2015).

The seeding period for both crops in Italy ranges from early spring to early June depending on the region and weather conditions. For this reason, in the same regions, farmers could choose between one crop, or another based on yield and technical-logistical reasons, as well as environmental sustainability concerns.

Hemp has a great positive impact on the environment, thanks to its ability to sequester atmospheric carbon (CO_2) throughout the growing season (Pervaiz and Sain, 2003), and phytoremediation, which cleans and improves soil improving quality and has great potential for removing heavy metals (Ahmad et al., 2016).

In addition, it is highly resistant to adverse conditions such as drought, pests, diseases, and weeds, and has a highly developed root system, which gives it great potential and versatility as it can be grown in many different growing conditions and almost always provides benefits to the agroecosystem, while also requiring low inputs for its cultivation (Adesina et al., 2020; Mancinelli et al., 2023). The importance of hemp becomes even greater when considered not only as a source of products and by-products of significant interest (oil, fiber, oilseed cake), but also for the ecosystem services it can provide (e.g. carbon sink) (Butkutė et al., 2015; Vosper, 2011). Indeed, in the absence of phytosanitary restrictions or allelopathic issues, and without alternative markets for selling them, agricultural residues and by-products from sunflower and hemp can be incorporated into farmland for economic and environmental benefits. This is due to the nutrients they contain, which can lead to a reduction in the need for fertilizer.

Various studies analyzed the environmental impact of the sunflower farm stage in Italy (Chiaramonti and Recchia, 2010; Forleo et al., 2018; Goglio et al., 2012; Montemurro and De Giorgio, 2005; Palmieri et al., 2014), in Slovenia (Al-Mansour and Jejcic, 2014), Chile (Iriarte et al., 2010) and Brasil (Matsuura et al., 2017). According to Spinelli et al., (2013) the agricultural phase represents the most impacting due to high energy requirements coming from mineral nitrogen fertilizers, phosphate fertilizers, and diesel oil. This aligns with the findings of previous studies on vegetable oil production from sunflowers (Spinelli et al., 2012; Spugnoli et al., 2012).

Nabavi-Pelesaraei et al. (2021) evaluated the environmental impact of the sunflower oil production in Iran using a mechanical cold pressing method, while Nucci et al. (2014) assessed the production of sunflower oil extracted with solvents.

Regarding industrial hemp, the majority of LCA studies in the literature on its cultivation are focused on biomass and fiber and their use in construction (Essaghouri et al., 2023; La Rosa et al., 2013; Pretot et al., 2014) or for paper production (González-García et al., 2010). Carbon footprint of hemp seed production was analyzed by different authors (Campiglia et al., 2020; González-García et al., 2010; Todde et al., 2022; Van der Werf, 2004) and according to our knowledge only Bernas et al. (2021) reported the CF of the hemp oil extraction process.

Using a case study approach (Adewale et al., 2019; Mensah et al., 2018; Pari et al., 2020) the objective of this study is to assess the CF of hemp and sunflower oil supply chains in the Mediterranean region by applying a life cycle assessment (LCA) approach, considering the incorporation into the soil of crop residues and by-products (oilseed cake). To the best of our knowledge, this study represents a novelty as none of the previous CF studies, focused on industrial hemp oil production in Italy, analyzed the entire oil production process, and evaluated the impact of the incorporation of residues and by-products into the soil. Consequently, this study fills a gap in the current scientific literature. The results of the present study could be useful to policymakers, farmers, and the agribusiness in decision making regarding the promotion and expansion of sustainable sunflower and hemp cultivation in Italy.

2. Materials and methods

In the following section, a detailed description of the case study and the methodology applied is given.

2.1. Case study description

The hemp and sunflower fields were located near Cassino (province of Frosinone, region of Lazio), in flatland and sandy soil, where rainfall in summer (April 1 – September 30) and winter (October 1 – March 31) averaged 424 mm and 417 mm, respectively, in 2022 (Climate Data, 2022). Data of the agriculture phase were collected by personal communication with local farmers, whereas oil processing were obtained from technicians and the manager of the oil mill. Consequently, this study is representative of the current circumstances present in the Lazio region regarding the average values of sunflower and hemp oil production.

In the present study, the cultivation technique consists of preparing the soil for both crops by plowing, followed by harrowing and rolling twice before sowing. Basic fertilization was applied to both sunflower and hemp, and top fertilization was utilized only on hemp. The Sunflower plants were weeded chemically, while weeds were controlled mechanically by harrowing for hemp. Chemical pest control was applied only to hemp, as well as artificial drying of the seed, while for the sunflowers this process was carried out in the field. The different cultivation practices are carried out by the farmer. The hemp harvesting was carried out by a contractor.

The harvested oilseed was transported to the nearest oil mill where the oil was extracted by mechanical cold pressing. At the oil mill, the sunflower seeds arrived with a moisture content of 10 % and were ready to be pressed, while the hemp seed had a moisture content of about 35 %, so an additional drying phase was required before pressing. The drying phase of the hemp took place in a static oven that processes 2.5 to 3 Mg of seeds per cycle that lasts 10 h consuming methane gas and electricity. The sunflower and hemp seeds were pressed using a continuous screw press with a capacity of 150 kg h^{-1} and driven by a 9 kW electric motor. Due to the different characteristics of the seeds, pressing hemp required an actual consumption of 8 kWh, while pressing sunflower seeds required a consumption of 7 kWh. Cold pressing is the most common technique for obtaining seed oil because of its simplicity. However, the press technique implies that a small amount of oil remains in the oilseed cake, which results in lower oil yield. It is known that the efficiency of oil extraction can vary significantly depending on specific gravity of the seeds: in the present study, it was considered 15 % for hemp and 35 % for sunflower. The extracted oil obtained is filtered with a plate filter press before being stored for sale.

2.2. Management of crops and by-products

Sunflower (*Helianthus annuus,* L.) is an annual oilseed crop grown in temperate and subtropical climates mainly for its seeds and edible oil. Its oil is highly valued compared to other vegetable oils due to the higher content of unsaturated fatty acids and bioactive compounds (e.g. tocopherols and phytosterols) (Debaeke and Izquierdo, 2021). A sunflower cultivar that has been widely used in Europe and especially in Italy is Experto. It has a stable plant with a convex head with high photosynthetic efficiency due to an extensive and vigorous leaf apparatus. Experto has a high yield of achenes and oil, a good hectoliter weight, and a high content of oleic acid. This variety develops its productive potential best under conditions of medium–high fertility. In terms of production, sunflower is generally used to produce edible food oil and oilseed cake for animal feed, with crop residues incorporated into the soil to prepare the ground for subsequent harvests.

Hemp (*Cannabis sativa* subsp. *Sativa,* L.) is used for various products and by-products, from cannabidiol oil to food, furniture, textiles, building materials, animal bedding and feed. The growing interest in sustainable materials and the comeback of hemp have led many farms and companies to take an interest in this fast-growing plant. The most promising new products are biofuel, medicine, cosmetics, acoustic panels, and soil contamination tools. The weaknesses for developing a market for hemp-derived products are mainly the high cost and the need for specific machinery for processing (Dhondt and Muthu, 2021). The choice of the destination of hemp stalks (fiber) depends on market conditions, especially the proximity between the farm and processing plants, to reduce transportation costs, energy supply costs and purchase prices required by the industry. Hemp varieties approved for cultivation are divided into dioecious and monoecious varieties. These are the result of breeding aimed at increasing seed production by distinguishing the destination of the crop. In fact, for the extraction of fibers and shives from the stems, dioecious varieties such as Carmagnola and Fibranova are preferable. On the other hand, if the cultivation aims at seed production, monoecious varieties must be used. Currently, Futura 75 is the most used monoecious variety in Italy.

If conditions are not favorable for conversion, an alternative may be to incorporate the biomass into the soil to increase soil fertility and carbon sequestration, thus saving chemical fertilizers for the following harvests.

2.3. Carbon footprint methodology

CF is a single-issue impact assessment method used to quantify the pressure of human activities on the environment in terms of equivalent carbon dioxide (CO_2-eq) emissions (Wiedmann and Minx, 2008).

In the present study, the carbon footprint of sunflower and hemp oils were calculated according to the standard ISO 14067:2018 (ISO, (International Organization for Standardization), 2018), in a manner consistent with the International Standards on Life Cycle Assessment methodology ISO 14040 and ISO 14044:2006 (ISO, 2006a, 2006b) from the cradle to gate of the oil mill using an attributive approach (Ekvall et al., 2016; Palmieri et al., 2017b; Pari et al., 2021; Sperandio et al., 2021). Said methodology includes the following steps: a) goal definition and scoping: defining the objectives of the study, functional units (FU), and boundaries of the system; b) life cycle inventory: primary and secondary data collection; c) life cycle impact assessment: evaluating the potential environmental impacts; d) life cycle interpretation and potential improvements.

The assessment was performed using SimaPro 8.0.2 software (PRé Consultants, The Netherland, NL) and the life cycle emission factors of the associated Ecoinvent 3 database (Ecoinvent, 2015), while following the IPCC GWP 100y v.1.02 method.

2.3.1. Goal and scope definition

The goal is to assess and compare the CF of sunflower and hemp oil supply chains considering the incorporation of all crop residues and by-products in the soil. The hot spots in the production life cycle that contribute significantly to greenhouse gas (GHGs) emissions have been identified.

The boundary of the supply chains analyzed includes all the agricultural processes that occur during sunflower and hemp cultivation and the subsequent oil extraction phase at the oil mill (see Fig. 1).

As suggested by Notarnicola et al. (2015), a functional unit (FU) can be used to identify the crop that generates the largest negative externalities per unit area, regardless of crop productivity. Therefore, a cultivated area of 1 ha was used as FU to compare the sustainability of the oil crops analyzed at field stage. Considering a mass-based FU is quite common in LCA studies (Palmieri et al., 2017a; Pari et al., 2020; Salomone et al., 2015) and it allows a comparison between different vegetable oil supply chains. Furthermore, 1 kg of cold-pressed seed oil produced was used as the FU for comparing the environmental impacts of the two seed oil supply chains.

2.3.2. Life cycle environmental inventory

Technical information on agricultural practices was used as primary data for the life cycle inventory analysis. The cultivation methods for both crops follow the agronomic guidelines for integrated production issued by the Lazio Region administration in 2020, with particular attention to weeding, plant protection and fertilization. Data related to sunflower and hemp yields, equipment characteristics and their field capacities, fuel and lubricating oil consumptions, type and amount of fertilizers, chemicals, and seeds used, and input used for oil production were collected by personal communication with local farmers, technicians and the manager of the oil mill (see Table 1). The seed yields of sunflower and hemp were 2.4 Mg ha^{-1} and 0.6 Mg ha^{-1}, respectively. Secondary data on upstream processes (i.e., tractor and machinery production, maintenance and disposal of tractor and machinery, fertilizer, and chemical production) were obtained from the Ecoinvent database (v 3.0).

2.3.3. Life cycle impact assessment

The amount of carbon dioxide (kg CO_2 ha^{-1}) in the exhaust emissions generated by agricultural tractors and combine harvesters were calculated by multiplying the fuel consumption (kg ha^{-1}) by an air emission factor of 2.6 (kg of CO_2 emitted per kg of diesel fuel consumed) (Grace et al., 2003; Lal and Stewart, 2015).

The direct emissions generated by the fertilizers and herbicides used were calculated using models and scientific software. In particular, the EFE-So software (v 2.0.0.6; Fusi and Fusi, 2015) was used to calculate N_2, NO_3^-, NH_3, and N_2O direct emissions generated by fertilizers during soil bio-geochemical cycles, according to the model of Brentrup et al. (Brentrup et al., 2000). CO_2 emissions from urea fertilization were calculated according to (De Klein et al., 2006). Herbicide emissions to air, surface water, and groundwater were assessed by the PestLCI 2.0 model (Dijkman et al., 2012).

A truck with a transport capacity of less than 3.5 Mg was used to transport the oilseeds from the field to the oil mill (50 km far from the fields) and the oilseed cake from the oil mill to the field.

2.3.4. Life cycle interpretation and potential improvements: Base analysis and sensitivity analysis

In the present study two analysis was assessed:

a) In the base analysis, no allocation was made for either sunflower or hemp supply chains, and all environmental impacts were attributed to seed oils. Since there is no market for by-products such as oilseed cake and fibre in the study area, farmers were left with no choice but to either

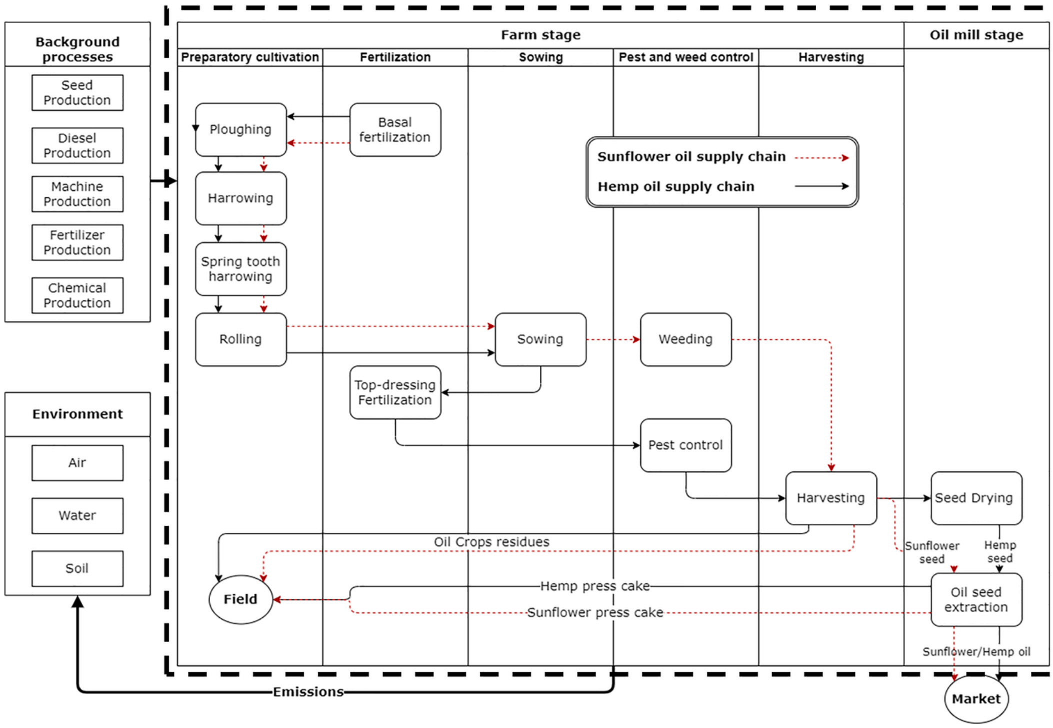

Fig. 1. System boundaries for *Helianthus annus*, L. and *Cannabis Sativa*, L. cultivation and seed milling for sunflower and hemp oil production (the dashed line represents the boundaries of the system analyzed).

dispose of these by-products or incorporate them into the agricultural soil. The incorporation of agricultural residues and oilseed cakes affects the biological, chemical and physical properties of the soil, as they are the main source of nutrients for the heterotrophic bacteria of the agro-ecosystem, which play a fundamental role in the cycling of organic matter (Voroney et al., 1989).

It is widely recognized that the fertilizer application stage causes the highest environmental impact during crop production (Alaphilippe et al., 2016; Bacenetti et al., 2016; Brandão et al., 2011; Campiglia et al., 2020; Forleo et al., 2018; Palmieri et al., 2017a; Ruviaro et al., 2012). When the residual biomass is incorporated into the soil, the macro-nutrients required to restore soil fertility correspond only to the nitrogen, phosphate, and potassium removed with the harvested seeds. Reincorporating oilseed cake into farmland can further reduce the necessary macro-nutrients. Organic biomass incorporation can therefore reduce the need for fertilizers, leading to a decrease in indirect greenhouse gas emissions. Moreover, incorporating organic matter into the soil results in the long-term storage of carbon in the humified biomass, particularly when practiced under agroecological management. In the study, it was assumed that all biomass generated along the supply chains, except for the extracted seed oil, would be returned to the field and incorporated into the farmland. The macro-nutrient contents in crop residues and by-products (N, K_2O and P_2O_5) incorporated in farmlands were included in the CF calculation as avoided products (urea as N, triple superphosphate as P_2O_5, and potassium sulphate as K_2O). According to (Deibert and Lizotte, 1982), sunflower oilseed cake contains 3.66 % nitrogen (N), 1.10 % phosphorus (P_2O_5) and 1.62 % potassium (K_2O). Sunflower stalks contain 1.40 %, 0.18 %, and 1.87 % N, P_2O_5, and K_2O, respectively (Babu et al., 2014). In hemp flour (obtained by oilseed cake milling), the N, P_2O_5, and K_2O contents are 5.44 %, 1.16 %, and 0.86 % respectively (Callaway and Pate, 2009). In hemp fibre, the contents of N, P_2O_5, and K_2O are 0.72 %, 0.06 %, and 0.11 %, respectively (Heard et al., 2007).

b) Furthermore, a sensitivity analysis was performed to assess the environmental impact of seed oil supply chains in the event that by-products and residues were sold in a potential market in the region, requiring an allocation procedure. According to ISO 14040, physical relationships should be prioritized when possible, or an economic allocation should be used if physical relationships cannot be applied to the system. However, for the sensitivity analysis, mass allocation was not deemed appropriate as it would not accurately reflect the effects attributed to the seed oil, which is the main product, since by-products (fiber and oilseed cake) represent the majority of the biomass and would skew the results. Also, Ardente et al. (2012) pointed out that the results of economic allocation may be more rational in systems where large quantities of by-products with low economic value are produced (Ardente and Cellura, 2012). For this reason, in the present study the sensitivity analysis was conducted using an economic allocation of emissions based on the mass and market price of sunflower and hemp seed oils (main products of the supply chains) and the market values of macronutrients contained in oilseed cakes and residues (by-products of the supply chains), according to the methodology used by Zampori et al. (2013).

Ex-farm prices for sunflower and hemp seeds were 0.47 € kg^{-1} (AGER - Associazione Granaria Emiliana Romagnola, 2022) and 1.50 € kg^{-1} (Cartechini, 2022), respectively. Sunflower oil is priced at 1.89 € kg^{-1} while hemp oil is at 21.5 € kg^{-1} (Cartechini, 2022).

The economic value of by-products was calculated based on their nitrogen, phosphorus and potassium content and market prices for fertilizers (see Table 2).

2.3.5. *Soil carbon sequestration*

Soil carbon (C) sequestration contributes about 89 % of the global mitigation capacity of agriculture that could potentially play a very important role as a C sink (Metz et al., 2007).

Organic carbon has an essential positive function for many soil properties, including aggregation and stability of soil particles with the effect of reducing erosion, compaction, and surface crust formation; it effectively combines with numerous substances, improving soil fertility; it increases microbial activity and plant availability of nutrients such as nitrogen and phosphorus. A considerable proportion of cultivated soils in the lowlands and hills of Italy have organic carbon concentrations

Table 1
Principal technical elements considered in the sunflower (S) and hemp (H) life cycle analysis.

Field stage	Crop	Engine Power	Tractor	Lifetime	Working time	Fuel (Diesel)	Lubricant	Equipment	Lifetime	Tech. input 1	Tech. input 2	Tech. Input 3
Unit	type	kW	kg	h	h ha^{-1}	l ha^{-1}	kg ha^{-1}	kg	h	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Plowing	S - H	132	7500	12,000	1.17	33.17	0.282	700	3000	–	–	–
Basal Fertilization	S - H	74	5000	12,000	0.34—0.17	4.84—2.66	0.022	200	2250	131.4—65 *	58—130 ***	180—127 §
Harrowing	S - H	110	6000	12,000	1	23.65	0.2	500	5000	–	–	–
2nd Harrowing	S - H	110	6000	12,000	1	18.94	0.2	500	5000	–	–	–
Rolling	S - H	74	5000	12,000	0.33	2.25	0.043	400	5000	–	–	–
Sowing	S - H	88	5200	12,000	0.33	6.27	0.773	800	5000	5—12	–	–
Top-dressing Fertilization	H	74	5000	12,000	0.17	3.2	0.022	200	2250	143 **	–	–
Weeding	S	132	7500	12,000	0.45	12.8	0.105	1300	5000	3 #	–	–
Pest control	H	132	7500	12,000	0.45	12.8	0.105	1300	5000	4+	–	–
Combine Harvesting	S - H	294	13,500	10,000	0.87	55	0.46	–	–	–	–	–
Oil mill stage	Crop	Engine Power	Machinery	Lifetime	Material capacity	Fuel (CH_4)						
Unit	type	kW	kg	h	kg h^{-1}	m^3						
Drying phase	H	15			300	0.1						
Seed conveying	S - H	0.75										
Extraction phase	S - H	9			150							

* Urea; ** Ammonium nitrate; *** Triple superphosphate; § Potassium sulfate; # Glyphosate; + Copper sulphate.

between 1 % and 2 %, which is characteristic of arable systems; in mountainous soils, carbon concentrations are more often between 2 % and 5 % (locally between 5 % and 10 %). The amount of organic carbon stored in the top 30 cm of Italian soils, according to the regional data currently available, varies considerably among the different climatic regions and the various soil crops, ranging from 41.9 ± 15.9 Mg ha^{-1} in vineyards, to 53.1 ± 17.3 Mg ha^{-1} in arable crops and 63.3 ± 27.9 Mg ha^{-1} in rice fields, with a slight decrease from temperate to Mediterranean regions. The estimated national average content in arable land is 52.1 ± 17.4 Mg ha^{-1}, which is similar to the value reported for other European countries (50–60 Mg ha^{-1}) (ISPRA, 2012).

As noted by Paustian et al. (1997), an increase in crop yields allows for more carbon to accumulate in plant biomass or changes in the harvest index (Paustian et al., 1997). Increased carbon storage in the soil is favored by the greater residual inputs associated with these higher yields. For this reason, in this case study, the amount of residue returned to the soil was indirectly calculated based on crop yields. Specifically, the potential aboveground biomass (AGB) of sunflower was calculated by dividing the yield of 2.4 Mg_{dm} ha^{-1} by a harvest index of 0.33 (Turner and Rawson, 1982). The quantity of seed harvested was subtracted from the sunflower AGB, resulting in a total biomass (leaves and stems) of 4.9 Mg_{dm} ha^{-1}. Assuming a shoot-to-root ratio of 5.56 (Ma et al., 2017), the root biomass of sunflower remaining in the soil was 0.9 Mg_{dm} ha^{-1}.

The biomass of stems and roots that remained in the soil due to hemp cultivation was 13.2 and 2.4 Mg_{dm} ha^{-1}, respectively, assuming a shoot-to-root ratio of 5.46 (Amaducci et al., 2008).

Considering a carbon content in above- and below-ground sunflower residues of 42.5 % (Gyori et al., 2005) and in above- and below-ground hemp residues of 55.2 % (Butkutė et al., 2015) and 41 % (Amaducci et al., 2008), the potential storable soil organic C is 2.4 Mg for sunflower and 8.3 Mg ha^{-1} for hemp. An additional biomass fraction of 1.51 and 0.56 Mg ha^{-1} would come from sunflower and hemp oilseed cakes, correspondingly. With an organic carbon content of 37.48 % (Lisý et al., 2020), incorporation of sunflower and hemp oilseed cakes in the soil would result in an increased carbon stock of 0.59 Mg ha^{-1} and 0.28 Mg ha^{-1}, respectively.

Once in the soil, biomass is eventually converted to SOC pools through humification, which is the natural process of converting organic matter to humus through geomicrobiological mechanisms (Sharma and Garg, 2018). The proportion of biomass converted to humic substances is quite stable and can remain in the soil for a long period of time, depending on agronomic practices and soil management. In cultivated soil, the humus content generally declines over a period of 10 – 30 years, until a new equilibrium level is attained (Stevenson, 1972). In the present study, the effect of temporary carbon accumulation, resulting from the incorporation of all residues and by-products from the sunflower and hemp oil supply chains into the farmland provided in the Base analysis, was evaluated. In the sensitivity analysis, the roots are the proportion of biomass considered to remain in the field and be converted to stable humus.

In the present study, an average time frame of humus degradation of 25 years was assumed.

The literature reports a humification value between 0.06 and 0.30 for the above-ground parts and between 0.16 and 0.30 for the below-ground parts of straw cereals (Andriulo et al., 1999). A wetting coefficient of 20 % for sunflower residues was determined by Muzzi and Rossi, (2003). Andriulo et al. (1999) found that humification yields depend on the type of crop residues and vary proportionally to their lignin content (Andriulo et al., 1999). For this paper, the humification index was calculated according to the formula (1):

$$k_1 = 2.11 - 0.020 \bullet NDF - 0.024 \bullet HEM - 0.022 \bullet CEL + 0.008 \bullet LIG \quad (1)$$

where:

k_1 = humification index.

NDF = percentage of compounds soluble in neutral detergent, (% dry

Table 2
Mass and economic allocation factors for sunflower and hemp products and by-products.

	Product and by-product	Sunflower Yield	Mass allocation factor	Economic value	Economic allocation factor	Hemp Yield	Mass allocation factor	Economic value	Economic allocation factor
		kg_{dm} ha^{-1}	%	€ ha^{-1}	%	kg_{dm} ha^{-1}	%	€ ha^{-1}	%
Farm stage	Oil Seed	2400	33 %	1128.00	**84 %**	600	4 %	1500.00	**87 %**
	Fiber	4900	67 %	211.22	**16 %**	13,200	96 %	221.52	**13 %**
	Nitrogen content	11.0*		21.00		95.0#		181.82	
	Phosphorus content	9.1*		13.37		7.9#		11.68	
	Potassium content	91.6*		176.85		14.5#		28.02	
Mill stage	Seed oil	840	35 %	1587.6	**90 %**	90	15 %	1935	**96 %**
	Press cake	1560	65 %	183.32	**10 %**	510	85 %	70.26	**4 %**
	Nitrogen content	57.1**		109.23		27.7§		53.08	
	Phosphorus content	17.2**		25.32		5.9§		8.73	
	Potassium content	25.3**		48.77		4.4§		8.46	

* considering 1.40% of nitrogen (N), 0.18% of phosphorus (P_2O_5), and 1.87% of K_2O in sunflower fiber (Babu et al., 2014).
** considering 3.66% of nitrogen (N), 1.10% of phosphorus (P_2O_5), and 1.62% of potassium (K_2O) in sunflower press cake (Deibert and Lizotte, 1982).
# considering 0.72% of nitrogen (N), 0.06% of phosphorus (P_2O_5), and 0.11% of K_2O in hemp fiber (Heard et al., 2007).
§ considering 5.44% of nitrogen (N), 1.16% of phosphorus (P_2O_5), and 0.86% of K_2O in hemp press cake (Callaway and Pate, 2009).

matter).

HEM = content of hemicellulose, (% dry matter).

CEL = content of cellulose, (% dry matter).

LIG = content of lignin, (% dry matter).

Hemicellulose, cellulose, and lignin contents of 33.5, 38.5, 17.5 % (Sharma et al., 2002) for sunflower biomass and 16.0, 40.0, 15.0 % for hemp biomass were considered (Kuglarz and Grübel, 2018). Humification coefficients of 0.36 and 0.39 were obtained for hemp and sunflower residuous by-products returned to soil.

Theoretical values of biogenic CO_2 equivalent temporarily stored, were calculated by multiplying the fraction of stable carbon in the form of humus in the soil by the atomic weight of carbon dioxide equal to 44/12. The accounting for a delayed emission was calculated according to the method suggested in the ILCD Handbook that comprises a 100-year horizon (European Commission, 2010). In particular, the CO_2-eq temporary sequester in humified biomass was obtained by multiplying the number of years that the emission was delayed by the kg CO_2-eq by a factor of −0.01 (Mg ha^{-1} y^{-1}). In the ILCD Handbook the C stored for a period inferior to 100 years is treated in a separate report and not as part of the overall result.

In the sensitivity analysis, only the humified biomass from the root system was taken into consideration as temporary carbon storage for a period of 25 years. All other by-products were assumed to be sold on the market.

3. Results and discussion

The present study showed that the production of sunflower oil is less polluting than that of hemp oil. Thus, 1 kg of sunflower oil results in the emissions of 4.24 kg CO_2-eq, compared to 16.39 kg CO_2-eq to produce 1 kg of hemp oil (Table 3).

Many studies have examined sunflower cultivation in terms of greenhouse gases, while relatively few studies have analyzed hemp (Table 4). In most papers, the production of greenhouse gases has been linked to the use of fertilizers and various cultural practices.

According to Bernas et al. (2021), the total environmental impact of hemp oil (volume of edible oil) was about 60 % higher than that of sunflower oil (based on the combination of production and unit area). By looking specifically at the emissions generated by 1 kg of seeds produced (cradle to farm gate) rather than 1 kg of oil extracted (cradle to oil mill gate), we can observe that the difference in emissions between the two oilseeds is negligible. In fact, when residues and by-products are incorporated into the farmland, 1.46 and 1.55 kg of CO_2-eq are emitted per kg of sunflower and hemp seeds, respectively. The results are in line with those obtained in the literature and result in lower GHG emissions

Table 3
Carbon footprint of sunflower and hemp oil supply chains - ~~Base Scenario~~ (IPCC GWP 100y method). Unit: kg CO_2-eq per kg product.

Life Cycle Stages	Sunflower oil supply chain	Hemp oil supply chain
	kg CO_2-eq per kg oil	kg CO_2-eq per kg oil
Fild stage		
Basal fertilization_Sunflower	3.89	7.91
Plowing	0.12	1.68
Harrowing	0.08	1.21
Top dressing fertilization_Hemp	n.a.	6.48
Spring tooth harrowing	0.07	1.00
Sowing_Sunflower	0.03	0.61
Rolling	0.03	0.39
Pest control_Hemp	n.a.	1.37
Weeding_Sunflower	0.08	n.a.
Combine harvesting_Sunflower	0.19	2.69
Sub total field stage	**4.49**	**23.34**
Avoided fertilizers due to by-products soil incorporation		
Triple superphosphate, as P2O5, at regional storehouse/RER U	−0.07	−0.48
Potassium sulphate, as K2O, at regional storehouse/RER U	−0.20	−0.46
Urea, as N, at regional storehouse/RER U	−0.27	−6.93
Sub total avoided fertilizers	−0.53	−7.87
Sub total field stage with avoided fertilizers	**3.96**	**15.47**
Oil mill stage		
Seed drying	n.a.	0.30
Oil extraction	0.09	0.23
Sub total oil mill stage	**0.09**	**0.53**
Transport	**0.20**	**0.39**
Total CO_2-eq per kg oil	**4.24**	**16.39**
Carbon stored in humus as CO_2-eq per kg oil (25 years)	−1.19	−33.55
Total CO_2-eq emitted per kg oil (including C storage by humus)	**3.05**	**−17.16**

Table 4
LCA studies about sunflower and hemp production.

Study	Crop	Country	F.U.	GHG emissions
Al-Mansour and Jejcic, 2014*	Sunflower	Slovenia	kg CO_2-eq per kg seed	From 0.225 to 0.318
Chiaramonti and Recchia, 2010	Sunflower	Italy	kg CO_2-eq per kg seed	From 0.50 to 2.14
Figueiredo et al. (2017)	Sunflower	Portugal	kg CO_2-eq per kg seed	From 0.39 to 0.65
Forleo et al., 2018	Sunflower	Italy	kg CO_2-eq per kg seed	From 0.53 to 2.25
Goglio et al., 2012	Sunflower	Italy	kg CO_2-eq per kg seed	From 0.50 to 1.70
Iriarte et al., 2010	Sunflower	Chile	kg CO_2-eq per kg seed	0.89
Matsuura et al., 2017	Sunflower	Brazil	kg CO_2-eq per kg seed	7.2
Spugnoli et al., 2012	Sunflower	Italy	kg CO_2-eq per kg seed	0.994
Campiglia et al., 2020**	Hemp	Italy	kg CO_2-eq per kg seed	From 0.161 to 18.72
Van der Werf, 2004	Hemp	France	kg CO_2-eq per ha	2330
Van der Werf, 2004§	Hemp	France	kg CO_2-eq per kg seed	3.88

* Herbicides/pesticides and fertilizer production not included.
** Comparison beetwen GHG emissions of different hemp cultivars.
§ Considering an hypothetical productivity of 0.6 Mg ha^{-1} (yield of the present study).

than the average value of the literature reported in Table 4. The minimum emissions were founded by Al-Mansour and Jejcic (2014) in Slovenia with GHG emissions ranging from 0.2247 to 0.3184 kg of CO_2-eq per kg of sunflower seeds (Al-Mansour and Jejcic, 2014). In the latter case, the authors excluded emissions from herbicides/pesticides and fertilizer production, which in contrast were included in the present work. A recent study by Campiglia et al. (2020) compared seven monoecious hemp cultivars, three planting densities, and two nitrogen levels. The authors found that GHG emissions from hemp production varied widely (Table 4). According to Todde et al. (2022), 73 % of industrial hemp production emissions are attributable to diesel consumed, and 82 % to fertilizer used, while machinery of upstream manufacturing accounted for a minor proportion of the requirements (2–4 %). If we shift the functional unit from emissions per unit of product to emissions per unit of land area, the results demonstrate that sunflower cultivation is 73 % more impactful than one hectare of hemp cultivation, with GHG emissions of 3.49 Mg CO_2-eq ha^{-1} compared to 0.928 Mg CO_2eq ha^{-1} for hemp. Our results were in line with the studies of Forleo et al. (2018) on sunflowers. The lowest impact in sunflower cultivation was mainly due to a high yield, which allowed to distribute the environmental impact over a higher production, or to a lower amount of nitrogen fertilizer applied (Forleo et al., 2018). For both sunflower and hemp, cultivation is the most impactful stage. For sunflower, the cultivation phase is responsible for 4.49 kg CO_2-eq per kg of oil produced, and for hemp, 23.34 kg CO_2-eq per kg of oil. However, the nutrients incorporated into the soil with residues and by-products led to a reduction of −0.53 and −7.87 kg CO_2-eq per kg of sunflower and hemp oils, respectively.

The characterization of the processes permitted to identify the phases and elements with the greatest impact. For sunflower oil production, basal fertilization of the agricultural phase is responsible for 91.7 % of the total impact (3.89 kg CO_2 per kg of sunflower oil). All other processes, from plowing to harvesting of the product, are individually responsible for GHG emissions that are always less than 0.2 kg CO_2-eq per kg of sunflower oil produced. In contrast, for hemp, since fertilization occurred in two steps, 48.27 % was due to basal fertilization (7.91 kg CO_2-eq per kg hemp oil) and 39.54 % was due to top dressing (6.48 kg CO_2-eq per kg hemp oil). About 70 %, and 20 % of the GHGs emitted to produce 1 kg of sunflower and hemp oil, respectively, were due to biogeochemical processes of denitrification of nitrogen fertilizers in the soil. Forleo (2018) found that high GHG emissions are mainly caused by the volatilization of nitrogen as nitrous oxide (N_2O), which is mainly influenced by agroecological conditions and the use of urea fertilizer, as also observed in other studies (Forleo et al., 2018; Scrucca et al., 2020). Dal Belo Leite et al. (2015) stated that an efficient way to limit nitrogen losses from soil profiles and reduce pollution is to improve the synchronization between nitrogen supply and demand and to use slow-release fertilizers. In fact, the type of fertilizer used can reduce the volatilization of nitrogen, and Cantarella et al. (2003) observed a 95 % reduction in emissions by replacing urea with ammonium nitrate. According to Figueiredo et al. (2017), an increase in inputs does not necessarily result in increased productivity and sustainability for sunflowers. It is recommended to use a nitrogen fertilization of 50 kg N ha^{-1} to achieve a good balance between production, nitrogen use efficiency indices, and a lower risk of pollution. For hemp cultivation, nitrogen is considered the most important nutrient. In fact, the application of nitrogen fertilizer has a positive effect on the height of the hemp plant, fiber biomass, yield and protein content in seeded varieties. In the first month of hemp growth, 79 % of the total N is taken up, corresponding to 3 to 4 kg ha^{-1} (Ivonyi et al., 1997).

In addition, N application after sowing or by split method did not increase stalk yield compared to N distribution at sowing. Moreso, no yield increase was observed at more than 150 kg ha^{-1} nitrogen (Finnan and Burke, 2013). In this context, the study conducted by Struik et al. (2000) also concluded that the growth of hemp on nitrogenous soils responded only slightly to nitrogen fertilizer. Application of an excessive amount of nitrogen can lead to rapid elongation of the stem, which poses the risk of lodging (Desanlis et al., 2013). On the other hand, insufficient nitrogen content leads to yield losses, and several studies have confirmed that nitrogen fertilizer application should be determined based on initial soil fertility and real needs for the crop (Adesina et al., 2020) to ensure maximum results with minimum emissions.

Tillage and harvest are responsible for the highest emissions after fertilization. Tillage practices impact sunflower oil production by 11.5 %, however, they have a greater impact on hemp oil production, with a 42.5 % impact. The harvesting phase had an impact of 4.43 % (0.19 kg CO_2-eq) and 16.4 % (2.69 kg CO_2-eq) per kg of sunflower and hemp oil, respectively. This share of GHG emissions due to tillage and harvesting is mainly due to direct emissions of engine exhaust to the atmosphere rather than emissions related to the production of agricultural machinery and diesel. In fact, both emissions related to the production of equipment and tractors (0.8 % − 0.03 kg CO_2-eq per kg sunflower oil - and 3.0 % − 0.49 kg CO_2-eq per kg hemp oil) and the production of diesel consumed during cultivation practices (2.22 % − 0.09 kg CO_2-eq per kg sunflower oil - and 8.33 % − 1.37 kg CO_2-eq per kg hemp oil, including all practices) had a relatively small impact. According to the results, 2.86 kg of sunflower seeds are required to extract 1 kg of sunflower oil compared to 10.3 kg of hemp seeds required to extract 1 kg of hemp oil. From an agricultural land perspective, 11.9 m^2 of land is required to produce 1 kg of sunflower oil, while 171 m^2 is required to produce 1 kg of hemp oil. In other words, 93 % less land is required to produce sunflower oil than for the production of hemp oil, resulting in lower impacts and GHG emissions. The significant difference between the CF results of the two supply chains can be attributed mainly to two factors: yield and extraction efficiency. On average, 2.4 Mg of seeds were obtained from one hectare of sunflower cultivation with an extraction efficiency of 35 %, while 0.6 Mg of seeds were harvested from hemp cultivation with an extraction efficiency of 15 %. Although the environmental impact of hemp oil production is greater than that of sunflower oil production, Bernas et al. (2021) observed that hemp production has several significant environmental benefits. Reducing soil erosion is one benefit of hemp that was not considered in this study. Hemp can improve and stabilise barren land by reducing weed pressure and soil erosion, unlike sunflower, which falls into the category of high erosion risk crops. Another advantage is the high carbon storage. An important aspect affecting the impact of global warming is the change in soil carbon as a result of different agricultural management practices (Queirós et al., 2015). The limited tillage practice reduces soil disturbance, leading to an increase in soil organic carbon (SOC). This increase in SOC helps to further mitigate climate change (Iordan et al., 2023). Hemp cultivation can sequester up to 2500 kg of CO_2 per hectare annually (Żuk-Gołaszewska and Gołaszewski, 2020). According to Halvorson et al. (2002), the annual cropping system with sunflowers sequesters an estimated 854 kg CO_2 ha^{-1} per year with no-till, compared to 92 kg CO_2 ha^{-1} with minimum tillage and a loss of 517 kg CO_2 ha^{-1} with traditional tillage (Halvorson et al., 2002). Sequestration of C in soil involves increasing the SOC pool by converting biomass to humus. It should be emphasised that biomass humification in SOC requires the availability of nutrients, similar to biomass production through photosynthesis (Lal et al., 2018). "Additional nutrients required are N, P, S, and other minor elements. Assuming an elemental ratio of 12:1 for C:N, 50:1 for C:P, and 70:1 for C:S, sequestering 10,000 kg of C into humus will require 25,000 kg of residues (40 % C), 833 kg of N, 200 kg of P, and 143 kg of S." (Lal et al., 2018). According to the analysis of the carbon content in the soil incorporating biomass, the humification coefficient, and assuming a lifespan of the humification biomass of 25 years in the soil, in the present study the potential carbon storage of the results of the two studied crops is very interesting. In particular, soil incorporation could mean a reduction of 28 % of the GWP for sunflowers and even more for hemp, from 16.39 to −17.16 kg CO_2-eq per kg of produced hemp oil (Table 3), highlighting the potential capacity of hemp to sequestrate an interesting amount of carbon per ha per year (10.2 Mg C ha^{-1} y^{-1}).

Empirical evidence shows that there is no outlet for sunflower and hemp by-products in Italy, mainly due to logistical obstacles. We believe that this seemingly threatening situation can be turned into an opportunity. In the absence of receptive logistics and markets, sunflower and hemp supply chain by-products could be left entirely on the ground to convert conventional farmland into regenerative farmland and transform traditional farms into carbon farms. As the European Commission points out, sustainable land management is key to achieving the EU's goal of climate neutrality by 2050, as it increases the carbon sequestered and stored in plants and soils (European Commission, 2021). Within this framework, sunflower and hemp farmers can use carbon farming as an innovative business model, in which farmers are paid to implement climate-friendly farming practices.

3.1. Sensitivity analysis

The sensitivity analysis considered the products and by-products of hemp and sunflower cultivation and oil production sold on the market. According to various authors, economic allocation allows a better representation of the causality of the production process in the food sector (Ardente and Cellura, 2012; Beccali et al., 2010). In this analysis economic allocations were applied to verify how the distribution of the GHG emissions of the seed oils production to product and by-products, would affect the output (Table 4).

Carbon emissions are broken down into various stages of the production process. For both sunflower and hemp oil supply chains, the field stage contributes the most to carbon emissions, with basal fertilization being the largest contributor.

From an environmental perspective, allocating a portion of the emissions to supply chain by-products results in a 15 % reduction in the impact of producing sunflower oil. 94.8 % (3.39 kg CO_2-eq per kg of oil) of the emissions are due to the field phase, while only 2.2 % are due to the mechanical oil extraction phase. On the other hand, the CF of hemp oil has increased by 24 % for the economic allocation compared to the base analysis. In fact, even if GHG emissions are in part shared to the by-products (fiber and hemp oilseed cake), in the sensitivity analysis no avoided fertilizers were considered with a consequent increased impact. The 96 % (19.5 kg CO_2-eq per kg of hemp oil) of the emissions are due to the field phase while only 2.5 % are due to electricity and natural gas consumption during the seed drying process and oil extraction phase (0.51 kg CO_2-eq per kg of hemp oil). Thus, this alternative crop management has a smaller impact on sunflower than on hemp regarding the positive effect of burying residues and by-products. From a CF perspective, burying by-products in agricultural soil makes more sense for hemp than for sunflower. If we consider the carbon stored in the humus of the residues that inevitably return to the soil, even in this analysis, the total carbon emissions per kilogram of sunflower and hemp oils produced are 3.28 and 16.5 kg CO_2-eq, respectively. Therefore, carbon sequestration makes the present study more sustainable than at the results obtained from the sensitivity analysis for both sunflower and hemp oil production (Fig. 2). In the present study, hemp cultivation resulted in negative CO_2 emissions due to its high carbon sequestration. This makes hemp more sustainable than sunflower in terms of its impact on climate change.

4. Conclusion

The aim of the study was to investigate an environmentally viable alternative to the lack of by-product infrastructure and supply chains in the south of the Lazio region, for hemp and sunflower cultivation.

The CF analysis of sunflower and hemp oil supply chains was conducted to identify the focal points in the production life cycle that contribute significantly to climate change. The results of the analysis show that the production of sunflower oil is less polluting than that of hemp oil if carbon sequestration is not taken into account. Cultivation is the most polluting phase for both sunflower and hemp productions. Tillage and harvesting are also responsible for high emissions after fertilization. Sunflower oil requires significantly less land and fewer seeds than hemp oil, resulting in lower impacts and GHG emissions. The difference in CF outcomes between the two supply chains can be attributed mainly to yield and extraction efficiency.

On the other hand, considering the effect related to carbon sequestration in the soil, burying all by-products generally leads to lower emissions, and hemp can result in negative emissions of CO_2, creating a carbon sink effect. In fact, the sensitivity analysis shows that burying residues in agricultural soil has a stronger impact for hemp than for sunflower oil, whose CO_2 emissions are lower when the byproducts are sold on the market. These results have significant policy and managerial implications, as they highlight the profound impact of adopting carbon farming as an innovative business model in achieving the EU's goal of

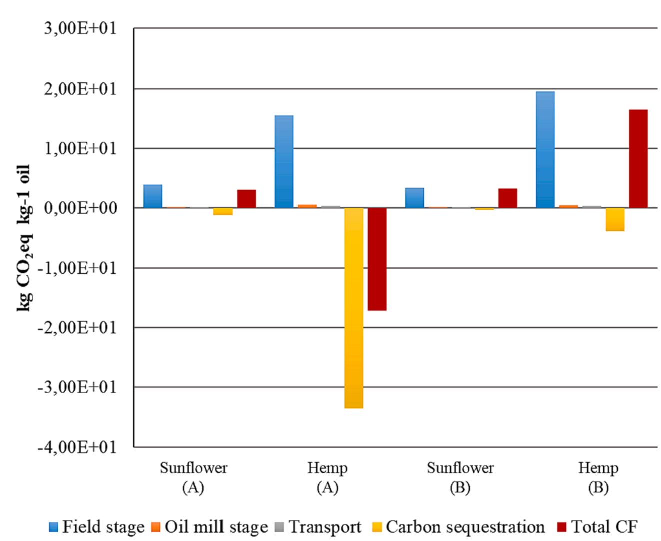

Fig. 2. Comparison of the carbon footprint of sunflower and hemp oil production between the results of the present study (A) and sensitivity analysis (B) (kg CO_2-eq kg^{-1} oil) with and without carbon sequestration.

climate neutrality by 2050. The limits of this case study may be overcome by conducting further research involving a greater number of farms and incrementing the timeframe. Further studies need to be conducted to investigate all aspects related to factors that potentially affect carbon sequestration, such as soil type, climate, and agricultural practices. This is because even slight changes in soil carbon stocks can contribute significantly to national GHG emissions. Subsequent research should address the economic viability of the supply chains presented in this paper, and the extent to which carbon farming can transform farms from net emitters to net capturers. In addition, the role of public policies, green public procurement, and voluntary carbon markets should be explored.

CRediT authorship contribution statement

Alessandro Suardi: Writing – review & editing, Supervision, Methodology, Conceptualization. **Ilenia Bravo:** Writing – review & editing, Supervision, Conceptualization. **Claudio Beni:** Writing – review & editing, Supervision, Conceptualization. **Patrizia Papetti:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Roberto Leonardo Rana:** Writing – review & editing, Visualization, Supervision, Methodology.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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