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Industrial hemp (*Cannabis sativa* L.) for phytoremediation: Energy and environmental life cycle assessment of using contaminated biomass as an energy resource

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ABSTRACT

The objectives of this study were to assess the environmental impacts of growing industrial hemp (*Cannabis sativa* L.) on the phytoremediation of heavy metal-polluted soil and using contaminated biomass as an energy resource. A life cycle assessment approach was adopted to evaluate the cumulative energy demand and climate change impact of using contaminated biomass for energy generation under 4 different scenarios. The industrial hemp supply chain scenarios include analyses of different subsystems (industrial hemp cultivation, seed processing, anaerobic digestion and biomass incineration for electricity generation) and different contaminated products harvested (seeds and straw, dried whole industrial hemp and fresh biomass for silage). As confirmed by a Monte Carlo simulation, the two scenarios that included anaerobic digestion and/or incineration of the contaminated biomass were the most energy-efficient and environmentally sustainable systems and obtained primary energy savings of 25.3 and 36.8 GJ ha^{-1}, respectively, while avoiding emissions of 579 and 641 kg CO_2e per reclaimed hectare, respectively. These results demonstrate the great potential of using contaminated areas for bioenergy (electricity) production while decreasing the exploitation of natural resources and pollutant emissions into the environment. Moreover, phytoremediation technologies combined with the energy valorization of biomass are recommended to change unproductive contaminated soils into exploitable and productive areas.

Introduction

Anthropogenic activities, especially those of the industrial and mining sectors, have left considerable areas of heavy metal (HM)-contaminated areas worldwide [33]. Due to their nonbiodegradable and persistent characteristics, HMs cause serious soil and water contamination and severe health hazards for living beings upon exposure [83]. In Europe, potentially polluting activities have taken place at an estimated 2.8 million sites, and only 24% of the sites have been inventoried [49,32]. Currently, only 28% of all registered sites have been investigated, which is a powerful precondition for deciding whether remediation is needed.

The term soil remediation refers to actions that are undertaken to limit the extent of soil contamination near hazardous waste sites to prevent exposure to harmful chemicals to people and other life forms [25]. Currently, there are many soil remediation techniques (e.g., physical, chemical, and biological) where the most appropriate method depends on the soil characteristics, contamination type, treatment depth and costs involved [87]. As reported by Dhaliwal et al. [25], among the different technologies that are used to ameliorate contaminated soils, phytoremediation is the cheapest and fastest technique to decontaminate soil with HMs. Moreover, phytoremediation has been shown to be a cost-effective and eco-friendly technology (with less threat to soil micro flora and fewer changes to the chemical properties of soil) compared to physicochemical soil reclamation methods [2,72]. Metal hyper-accumulator plants can accumulate large amounts of concentrated HMs

Abbreviations: AD, Anaerobic Digestion; ADP, Anaerobic Digestion Plant; BFPP, Biomass-Fired Power Plant; CED, Cumulative Energy Demand; CHP, Combined Heat and Power; DM, Dry Matter; GHG, Greenhouse gas; GWP, Global Warming Potential; HM, Heavy Metal; HSC1-2-3-4, Hemp Supply Chain 1-2-3-4; IPCC, Intergovernmental Panel on Climate Change; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; S1-2, Experimental Site 1-2; VS, Volatile Solids.

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in their biomass and remain healthy, which makes them suitable for the phytoremediation of HMs in contaminated soil [8].

Among the promising species that have been used for remediating HM-contaminated soils, the use of industrial hemp (*Cannabis sativa* L.) has shown promising phytoremediation potential in terms of morpho-physiological and metal accumulation responses [5,74,89], remediation capacity [18], trace element (Cd, Cu, Ni, Pb and Zn) phytoextraction [68] and the phytoremediation capability of wild weed [36]. In addition, industrial hemp grows in different climates and produces high biomass yields, and its roots grow deep into the soil, which allows the plant to penetrate deep into the soil and increases the efficiency of removing widespread contamination [4]. Linger et al. [60] found that industrial hemp accumulates HMs in all of its plant parts and that the highest contaminant concentrations accumulate in the leaves. This finding emphasizes the importance of plant management, treatment and disposal of contaminated biomass to avoid secondary pollution, since the methods that are used to recover HMs from plant biomass and/or the safe disposal of harvested plants are still limited [84]. The same study also suggested that in the future, more research must be conducted to provide technological improvements regarding the proper disposal of harvested contaminated biomass. Wu et al. [103] indicate that industrial hemp has been extensively applied, with appropriate pretreatments and investigations, to fields including bioenergy, paper production and construction materials. According to Zhang et al. [105], the postharvest management of plant biomass can be developed, which would include energy production, where the coupling of bioremediation techniques to bioenergy production yields far-reaching social and economic benefits [77]. Notwithstanding the fact that the phytoremediation of HM-contaminated soil is perceived as an eco-friendly technique, such phytoremediation activities might generate considerable environmental impacts, mainly due to the on-field activities, transportation and disposal or treatment of the biomass. To evaluate the environmental burdens of phytoremediation techniques, life cycle assessment (LCA) represents a valuable methodology to analyze the in-depth impacts [17]. Other studies have underlined the environmental implications of several bioremediation technologies. Witters et al. [100] found that phytoremediation technologies do not have the energy-consuming and CO_2-emitting drawbacks of conventional remediation activities that consist of soil excavation, chemical stabilization, incineration, vitrification and soil washing. Ali et al. [2] also emphasize that conventional remediation technologies may lead to the alteration of soil properties and the disturbance of microflora. In another work, Vigil et al. [94] argued that if the contaminated biomass was not valorized, then the sustainability of phytoremediation was questionable. An LCA methodology was also applied by Vocciante et al. [95] to evaluate the environmental sustainability of phytoremediation technology. The results emphasized the importance of correctly managing the disposal of the contaminated biomass that was produced, where biomass incineration could be more onerous than direct landfilling but would be viewed as a more sustainable choice if combined with energy production. Moreover, O'Connor et al. [69] found that phytoremediation at a site was resilient when faced with moderate sea level rises and other hydroclimatic effects that were induced by climate change. Despite the aforementioned studies conducted on phytoremediation, there is a lack of knowledge on assessing the energy and environmental impacts of such remediation techniques. Although the technical issues and suitability of industrial hemp for phytoremediation have been deeply analyzed, less attention has been given to the energy and environmental aspects of the entire supply chain. Despite the growing interest in industrial hemp cultivation, which is also supported by national and European founding and regulations, this 'new crop' suffers from current limitations, which start with the lack of knowledge of cultivation techniques, concerns by farmers about the legality of cultivation, and the scarcity of product processing plants, especially for the textile and fiber sectors, which limits its diffusion. Moreover, new studies are needed to overcome the current limitations related to the development of more sustainable industrial hemp supply chains.

The aim of this study was to assess and evaluate the energy and environmental impacts of growing industrial hemp (*Cannabis sativa* L.) for the phytoremediation of HM-polluted soil. Additionally, the use of contaminated biomass as an energy resource in 4 different valorization scenarios was also analyzed.

The three novel aspects of the performed analysis can be summarized as follows: i) to the authors' knowledge, none of the previous LCA studies evaluated the energy and environmental impacts of industrial hemp at each phase of the cleanup process; ii) the energy and environmental benefits of phytoremediation were evaluated under 4 different industrial hemp biomass valorization scenarios, which included analyses of different products harvested (seeds and straw, dried whole plant and fresh biomass for silage) and different subsystems, such as industrial hemp cultivation in HM-contaminated soils, with and without hemp seed processing, with and without anaerobic digestion of the contaminated products for electricity generation and biomass/digestate incineration in a biomass-fired power plant for electricity production; and iii) the work applied a broad approach in the analyses by including the entire supply chain of industrial hemp for phytoremediation in real sites that were contaminated by HMs.

Materials and methods

Goal and scope of the study

This study aims to assess the energy and environmental impacts of industrial hemp cultivation for the phytoremediation of HM-contaminated soil using industrial hemp biomass as an energy resource. An LCA methodology [44,45,42,43] was adopted to investigate the following:

- The field cumulative energy demand and environmental impacts of industrial hemp cultivation for the phytoremediation of HM-contaminated soils;
- The energy and environmental benefits obtained from using contaminated industrial hemp biomass as a renewable energy resource for anaerobic digestion and incineration (both for electricity generation through biogas combustion and with a steam turbine, respectively) when compared with conventional power sources; and
- The supply chain feasibilities of different industrial hemp biomass utilization scenarios for energy and environmental valorization.

Data source and analysis

The input–output data were collected by Agris Sardegna under the framework of the "CANOPAES" project at two experimental sites located in Sardinia (Italy). The first experimental site (S1) contains low levels of HM-contaminated soil, while the second experimental site (S2) contains high-level HM-contaminated soils (the soil Pb, Zn and Cd concentrations are far above the contamination thresholds that were established by Ministerial Decree 46/2019 [24]). At both experimental sites, the "Futura 75" industrial hemp cultivar was sown at a rate of 40 kg ha^{-1} and fertilized with 60 kg ha^{-1} nitrogen (Urea N 46%), while the irrigation water was distributed at a rate of approximately 4,500 m^3 ha^{-1} based on the thermopluviometric trend (year) and soil moisture content. The input–output data of the processes after the field gate were gathered from the most recent scientific literature and from the Ecoinvent database (Wernet et al., 2016). As recommended by Siregar et al. [86], to meet the data quality requirements, data verification must be conducted. The data adopted in this study were checked and verified according to the data quality parameters proposed by ISO 14044 [43]. Specifically, the data quality included the time coverage, geographical coverage, precision, completeness, representativeness, consistency, reproducibility, data sources, and information uncertainty. In addition, an uncertainty analysis was performed to address any parameter uncertainties and to test the robustness of the Life Cycle Impact Assessment (LCIA).

The Monte Carlo simulation method was conducted by using 1,000 Monte Carlo analysis runs. This analysis was carried out by collecting a set of uncertainties for the parameters that affected the variation of each scenario. Specifically, the uncertainties for industrial hemp cultivation, seed processing plants, anaerobic digestion plants, biomass-fired power plants and transportation were accounted for. Where available, uncertainty was explained by the results of this study (industrial hemp cultivation), while for the other subsystems, the mean and standard deviation were provided from the referenced sources or recalculated based on available published data.

Functional units, system boundaries and industrial hemp biomass utilization scenarios

The selected functional unit of this study consisted of 1 kg of dry matter industrial hemp product and 1 ha of phytoremediated area. An assessment of the cumulative energy demand and environmental impacts of each production phase, from raw material extraction, the manufacturing process, cultivation, transportation and biomass utilization, to the end of life, was analyzed in this study, and 4 different industrial hemp supply chain scenarios were designed (Table 1). The system boundaries of the 4 scenarios were defined from cradle-to-grave.

Scenario 1 - Industrial hemp supply chain scenario 1 (HSC1) includes, as shown in Fig. 1, industrial hemp cultivation (soil preparation and crop management) and harvesting of the crop at the full ripening stage of the seeds (September), with two main products obtained, namely, industrial hemp seeds and residual straw. These two products share the same on-field activities; thus, the energy and environmental burdens were distributed between these products by following the economic allocation method.

After transportation, the industrial hemp seeds were treated in a processing plant to obtain several final products (mainly oil and press cake), while the industrial hemp straw was pressed and delivered to an anaerobic digestion plant for biogas production. The biogas produced was used to generate electricity and heat, where a portion of the heat was used to dewater the digestate. Next, the dry digestate was transported to a biomass power plant to produce electricity for the grid.

Scenario 2 - Fig. 2 shows industrial hemp supply chain scenario 2 (HSC2), which consists of, as specified in HSC1, industrial hemp cultivation, management and harvesting of the seeds and straw, and the treatment of industrial hemp seeds in a processing plant. The industrial hemp seeds and residual straw share the same on-field activities; thus, the energy and environmental burdens were distributed between these products by following the economic allocation method. In this scenario, the straw bales from the field were transported directly to the biomass power plant for electricity generation.

Scenario 3 - Industrial hemp supply chain scenario 3 (HSC3) includes industrial hemp cultivation and then mowing the dried plants (September) to obtain a dried whole plant product (Fig. 3).

Industrial hemp straw bales, after transportation, were used as solid fuel in a biomass power plant to produce electricity for the grid.

Scenario 4 - Industrial hemp supply chain scenario 4 (HSC4) includes, as shown in Fig. 4, industrial hemp cultivation (soil preparation and crop management) and harvesting of the crop after the complete flowering stage (August) by using a self-propelled forage harvester to obtain a chopped whole plant with a short cutting length (20–30 mm). The industrial hemp biomass was transported to an anaerobic processing plant where after an ensiling process, the product was used as a substrate for biogas production. The successive steps of this industrial hemp supply chain scenario were the same as those presented for HSC1.

Table 1
Summary of the main characteristics of the 4 designed industrial hemp supply chain scenarios ("√" included; "X" not included).

Supply Chain Scenarios	Product Harvested	Seed Processing	Anaerobic Digestion	Combustion
HSC1	Seeds + Straw	√	√	√
HSC2	Seeds + Straw	√	X	√
HSC3	Dried Whole Plant	X	X	√
HSC4	Fresh Biomass	X	√	√

Life cycle inventory (LCI)

An LCI includes an extended set of inputs and outputs that are associated with the studied system. Analyses of the inventoried data were conducted by splitting the overall processes into 5 subsystems, as described below.

1- Industrial hemp field cultivation for the phytoremediation of HM-contaminated soil. A field-level dataset was obtained from on-site measurements that included the overall inputs (diesel fuel, seeds, and fertilizers), outputs (harvest yields of seeds, straw, and chopped biomass) and detailed descriptions of each cultivation activity for each designed scenario (HSC1-2-3-4). Specifically, the information consisted of the field task conducted, the type and power of the agricultural machinery used and the time spent per activity, which were collected for industrial hemp cultivation. The equations applied to assess the requirements for the amount of diesel fuel are available in the associated dataset (https://data.mendeley.com/datasets/p4btx7kptd/1).

The irrigation activities and amounts of seeds and fertilizers used were also included in the analyses. Moreover, as suggested in other energy and environmental studies, the indirect energy requirements of capital goods for on-field activities were included to obtain a broader overview of the examined system [23,92,93]. For these reasons, the embodied energy of the machinery and equipment that was used for the field operations was considered in this study.

2- Seed processing plants transform seeds into refined products. After the harvesting operations, the industrial hemp seeds were delivered to a processing plant for further treatment in scenarios HSC1 and HSC2. The industrial hemp seeds were immediately dried with air ventilation because improper moisture levels of the seeds may cause considerable problems in their conservation and in subsequent processing phases. The preprocessing activities consisted of sieving and ventilation by rotary sieves. Then, the industrial hemp seeds were processed in an expeller screw press to extract the oil and to obtain the cake byproduct. The cumulative energy demand and environmental burdens of industrial hemp seed processing were offset by the savings that were obtained from the replaced products. Industrial hemp oil and its byproducts are widely used in the nonfood sector to produce biofuels and other industrial products. The seed processing dataset for this work comes from the processing trials that were carried out and are still in progress at the experimental stations of Agris.

3- Anaerobic digestion plants for biogas production and energy conversion. The industrial hemp byproducts (straw) for scenario HSC1 and fresh industrial hemp biomass (whole chopped plants) for scenario HSC4 were used in an anaerobic digestion plant (ADP) for biogas production. Based on the available literature, it was assumed that the fresh industrial hemp biomass (moisture 65%) was ensiled at the ADP with a dry matter loss of 12% [54], while the industrial hemp straw bales were stored at the ADP. Both the industrial hemp silage and industrial hemp straw bales were mechanically pretreated with a cross-flow grinder before feeding the anaerobic reactor, and an energy expenditure of 12 kWh t^{-1} of feedstock was adopted [66]. The quantity and quality of the biogas may vary based on the input material compositions and operational parameter settings (e.g., the hydraulic retention times and digestion temperatures). A specific methane yield of 92 m^3 t^{-1} (volume at standard conditions) of volatile solids (VS) was adopted for the industrial hemp straw residues under mesophilic conditions (arranged from [7], while a value of 234 m^3 t^{-1} (volume at standard conditions) of

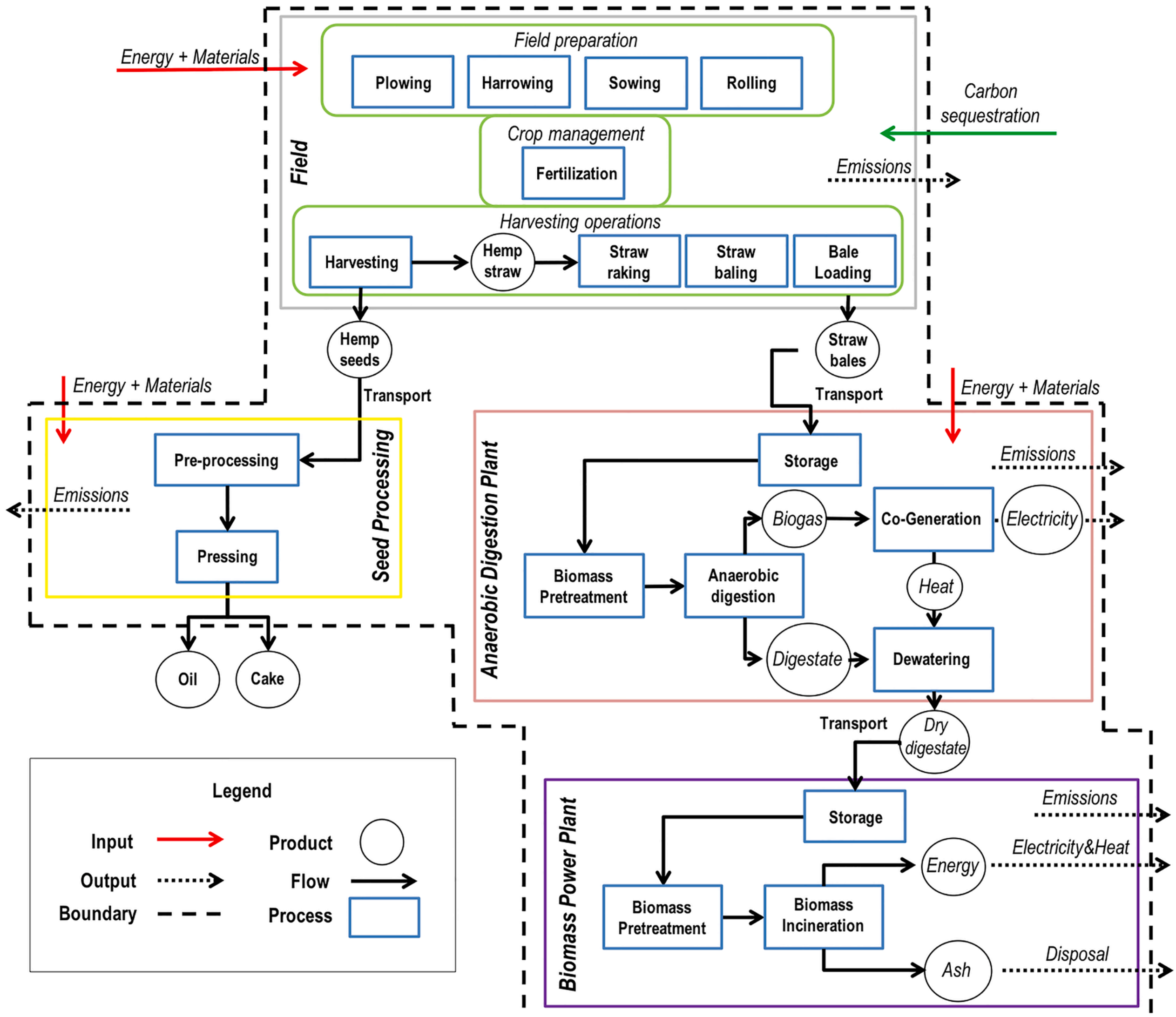

Fig. 1. System boundaries of industrial hemp cultivation for the phytoremediation of HM-contaminated soils – HSC1.

VS for the industrial hemp silage was used [52]. Moreover, it was assumed that 1.73% of the methane produced was lost as diffuse methane emissions in the combined heat and power (CHP) unit [59,79,96]. The produced biogas was converted into a CHP unit (considering 0.35 electrical efficiency and a lower heating value of 36 MJ m^3 of methane) for electricity and heat generation; electricity was conveyed to the national grid, while heat was used for dewatering the digestate. According to the national directive [27], the agronomic use of digestate, which is produced with the addition of biomass derived from contaminated areas, is not allowed, while the energy valorization of the digestate is encouraged after a rigorous dewatering process. Other studies have indicated that dewatering digestates improves their disposal (e.g., in landfills, composting and incineration), but the water content of the digestate should be reduced to 50–60% [99,102]. Several technologies are available to reduce the water content of digestates obtained from anaerobic digestion (AD), such as a belt conveyor dryer [9,78]. In this study, the heat from the CHP unit is used to dewater the digestate, since only a minor proportion of the heat produced from the CHP unit is used to maintain the optimal thermal conditions of the anaerobic reactor, while the remaining heat proportion is generally not exploited in commercial ADPs due to their locations in rural areas and because there are only a few potential heat consumers for bulk consumption [14]. For these reasons, in this study, the surplus heat that was produced from the CHP unit was released as waste heat into the atmosphere [65]. The production of capital goods (e.g., construction facilities, machinery, and equipment) was excluded from the inventory assessment of this study since the capital equipment of ADPs is commonly not considered due to their long life spans and low environmental impacts [30,50,88].

4- Biomass-fired power plant for industrial hemp biomass incineration and energy generation. The dewatered digestates from scenarios HSC1 and HSC4, the industrial hemp straw bales from scenario HSC2 and the dried whole plant bales from scenario HSC3 were incinerated in a biomass-fired power plant (BFPP) for electricity generation. The exploitation of the waste heat that was derived from the BFPP was not considered in this study since reliable energy and emissions factors were not available. Additionally, the limited availability of national district heating structures causes the exploitation of waste heat to be difficult to pursue. Accordingly, the BFPP dataset was compiled from the available scientific literature. The BFPP was assumed to have a life span of 20 years and a power (electrical) generation efficiency of 20%. In addition, due to the nonnegligible capital goods burdens, the cumulative energy demand and carbon emission impacts of BFPP upstream manufacturing were 0.35 MJ kWh^{-1} and 0.036 kg CO_2e kWh^{-1}, respectively [98]. The dewatered digestate and industrial hemp straw bales were stocked at the BFPP. The industrial hemp straw bales were mechanically pretreated

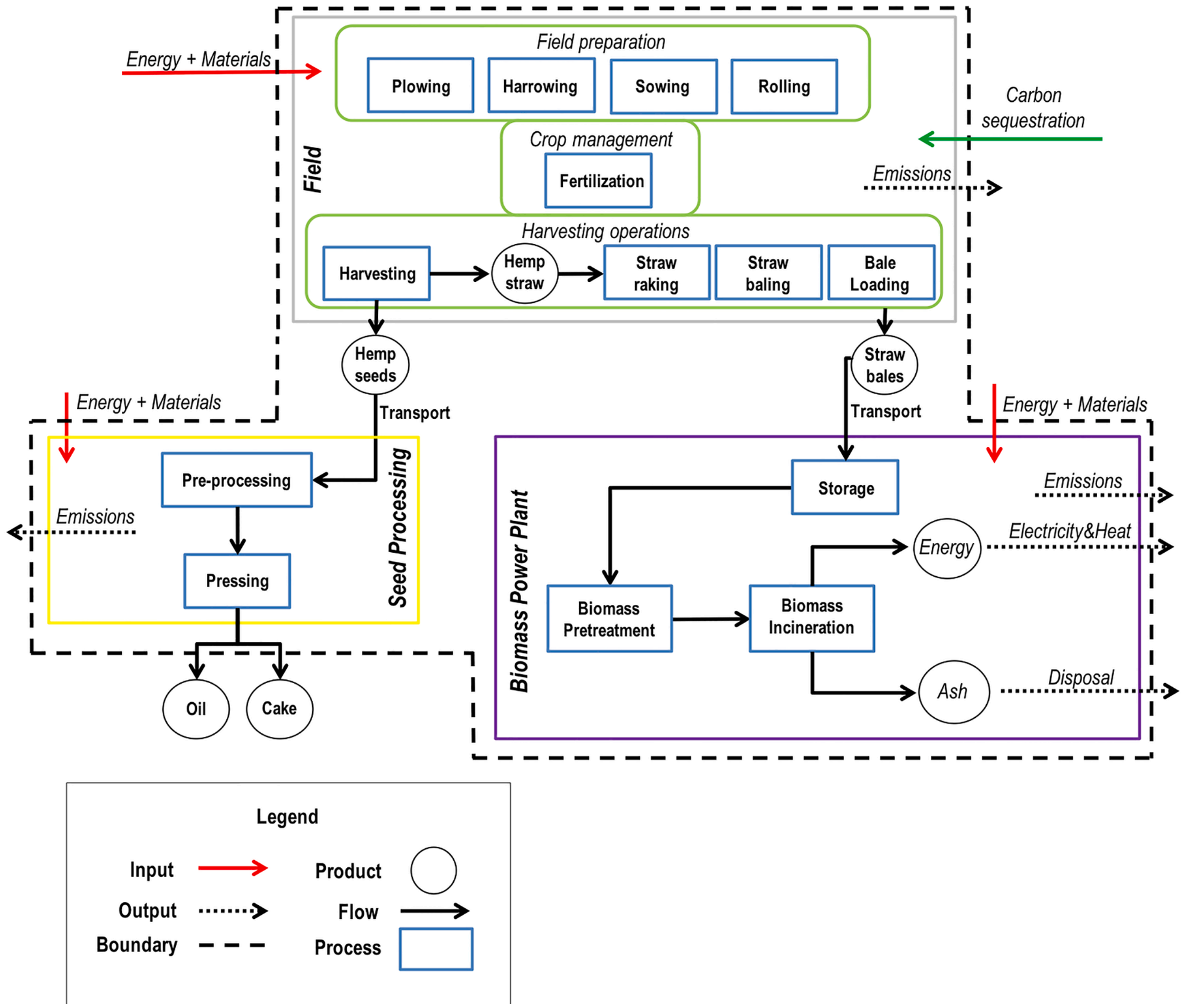

Fig. 2. System boundaries of industrial hemp cultivation for the phytoremediation of HM-contaminated soils – HSC2.

with a cross-flow grinder before incineration, with an energy expenditure of 12 kWh t^{-1} of biomass. The specific lower heating values adopted in the hemp supply chain scenarios are available in the associated dataset (https://data.mendeley.com/datasets/p4btx7kptd/1).

In this study, the BFPP employed a mixture of biomass in the furnaces; thus, the suitability of ash as a mineral soil amendment is unknown and requires further investigation. In fact, Cavalcanti et al. [16] and Ferreira et al. [34] found that the contribution of the final disposal of biomass ash was not significant or was excluded from the study boundaries. For these reasons, the disposal of biomass ash was considered to be outside the system boundaries. This aspect represents a limitation of the study.

5- Transportation phases. The transportation of the products among the different processing sites was included in the system boundaries of this study. The transportation data were obtained from the Ecoinvent 3 dataset (Wernet et al., 2016) and from onsite information. Specifically, the industrial hemp seeds (scenarios HSC1 and HSC2) and industrial hemp straw bales (scenario HSC1) were transported from the field gate to the seed processing plant (50 km) and to the ADP (20 km), respectively, and 16–32-t Euro 5 trucks for road transportation were used. The fresh industrial hemp biomass that was harvested in scenario HSC4 was transported to the ADP (15 km) by tractors (trailer 20 t). The dewatered digestates were delivered from the ADP to the BFPP (50 km) in scenarios HSC1 and HSC4 with 16–32-t Euro 5 trucks for road transportation. These trucks were also used in scenarios HSC2 and HSC3 for industrial hemp bale transportation from the field gate to the BFPP (60 km).

Impact assessment

The industrial hemp supply chain was evaluated from an energy and environmental point of view and considered the following impact categories: the cumulative energy demand (CED), which is largely used to analyze the primary energy (MJ) requirements of a given system, and climate change (CC), which quantifies the greenhouse gases (GHG) that are emitted by the production chain. Both categories include the entire life span of the system (from cradle to grave). As defined by the Intergovernmental Panel on Climate Change [41], the impact on climate change of each GHG emitted during the life cycle of a product was calculated by multiplying the mass of a given gas by its global warming potential (GWP) using a 100-year time horizon. The GWP represents the contribution of a GHG to the greenhouse effect and is represented in kg of carbon dioxide equivalent (CO_2e). The renewable electricity produced in the designed scenarios replaced the grid national electricity assuming 9.21 MJ kWh^{-1} [63] as energy equivalent and 0.288 kg CO_2e kWh^{-1} [46] as emission factor. Further energy equivalents and emission factors used in this study are available in the associated dataset (https://data.mendeley.com/datasets/p4btx7kptd/1).

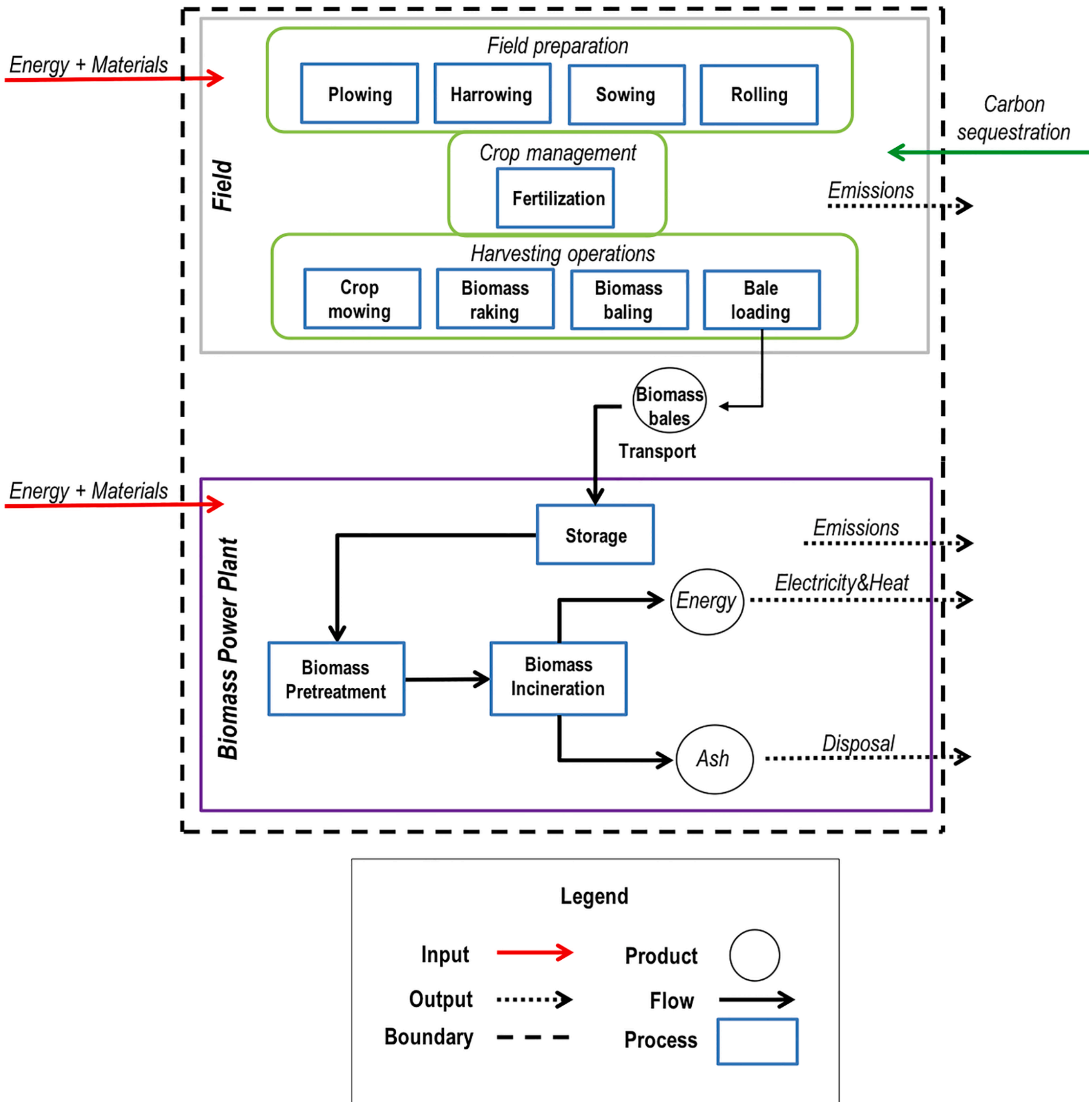

Fig. 3. System boundaries of industrial hemp cultivation for the phytoremediation of HM-contaminated soils – HSC3.

Results

Experimental field subsystem

The data collection and analysis allowed us to quantify the input amounts that were employed for industrial hemp cultivation and harvest. Specifically, Table 2 summarizes the main results of the two real HM-contaminated soils with respect to the amounts of cultivation inputs, diesel fuel requirements and machinery working times for each designed industrial hemp supply chain scenario. Overall, the on-field activities were analyzed for each designed scenario where the total diesel fuel requirements accounted for, as the average of S1 and S2, 106 kg ha^{-1} for scenarios HSC1 and HSC2, 96 kg ha^{-1} for scenario HSC3 and 110 kg ha^{-1} for scenario HSC4.

The levels of diesel fuel consumption among the 4 designed scenarios indicate that the plowing and harvesting operations were the most demanding activities, while rolling and fertilization accounted for a minor proportion of the fuel requirements. These results are related to the type of on-field activity and the working time and power of the machinery adopted in each scenario. The average rated power was higher in scenario HSC4 (142 kW ha^{-1}) and was lower in scenarios HSC1-2 (82 kW ha^{-1}) and HSC3 (67 kW ha^{-1}). The average working times ranged from 7.2 to 7.9 h ha^{-1} for scenarios HSC3 and HSC4, respectively.

The 4 designed scenarios for the field subsystem allowed us to harvest different industrial hemp products in HM-contaminated soil. The industrial hemp cultivation outputs in the HSC1-2 scenarios for S1 and S2 were harvested seeds with yields of 600 and 300 kg$_{FM}$ ha^{-1}, respectively, and residual straw amounts of 5000 and 2600 kg$_{FM}$ ha^{-1}, respectively. In scenario HSC3, the harvested industrial hemp product consisted of dried whole plants with production yields of 6640 and 3335 kg$_{FM}$ ha^{-1} for S1 and S2, respectively. Fresh industrial hemp was harvested at blooming in scenario HSC4 and obtained 18,000 and 9000 kg$_{FM}$ ha^{-1} of fresh biomass with an average dry matter content of 35%. The observed difference in the yields for the two experimental sites was mainly dependent on the soil contamination levels. In S1, there was slight contamination by HMs that was essentially due to Pb and Zn; at site S2, the pollution was much more significant due to very high Pb, Zn, Cd and Co concentrations. These soil contamination levels negatively affected the growth of industrial hemp and crop yields, as reported by Pietrini et al. [74].

The amounts of the total inputs that were employed in the field subsystem and for the harvested industrial hemp products were further analyzed by applying the corresponding energy equivalents and

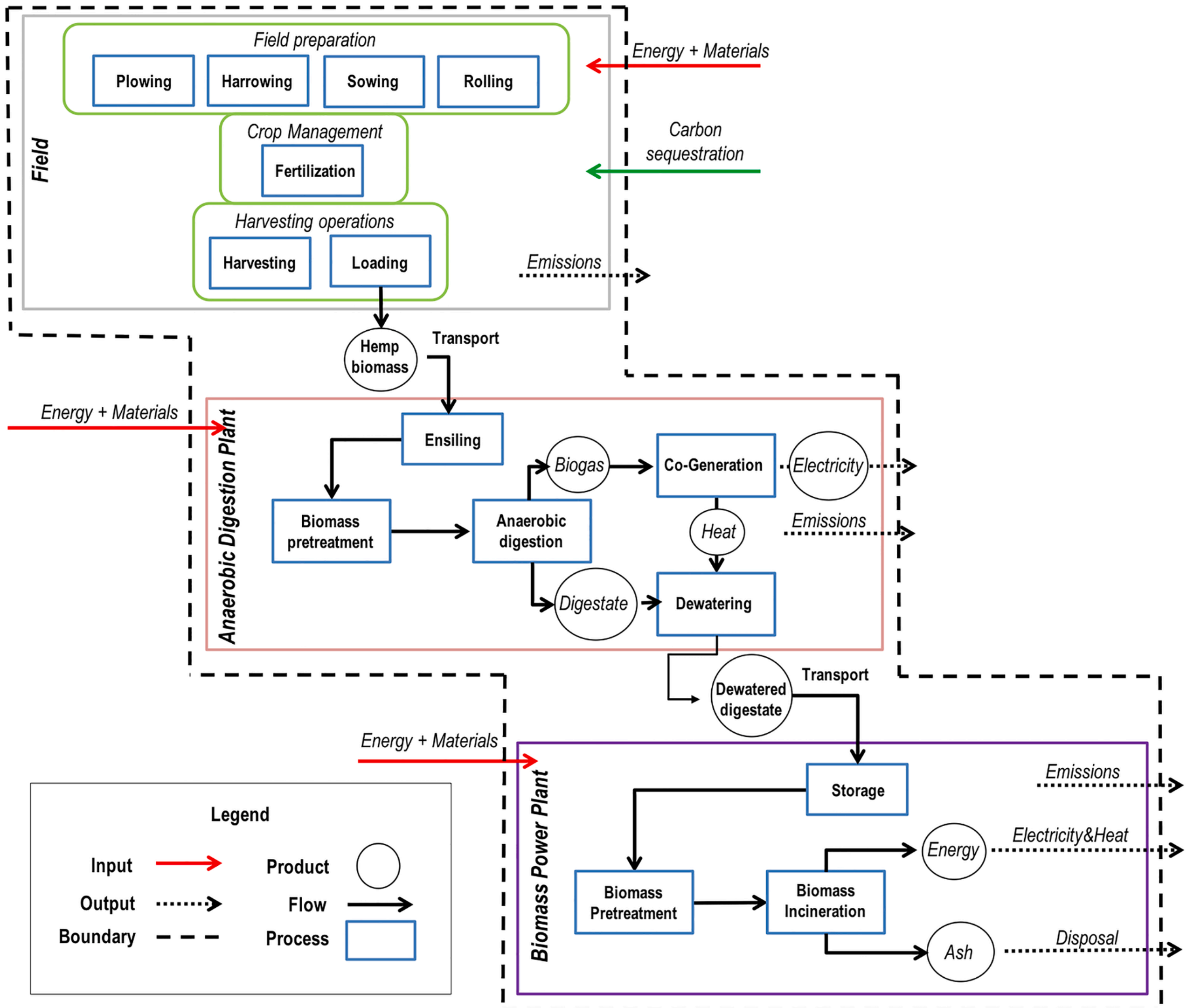

Fig. 4. System boundaries of industrial hemp cultivation for the phytoremediation of HM-contaminated soils – HSC4.

emission factors.

By considering the overall inputs that were employed in the field subsystems, the primary energy accounted for 1.91 MJ and 116 gCO_2e of the fresh industrial hemp biomass in S1, and 3.64 MJ and 220 gCO_2e were both expressed as per kg of dry matter (DM) for the S1 and S2 sites, respectively. Industrial hemp seeds comprised the highest proportion of the energy and carbon emissions and accounted for 17.86 MJ kg^{-1} and 1041 gCO_2e kg^{-1} for the S1 site and 33.31 MJ kg^{-1} and 1988 gCO_2e kg^{-1} for the S2 site. The lowest impacts were obtained for residual straw, with a primary energy demand of 1.17 and 1.44 MJ kg_{DM}^{-1}, while the carbon dioxide emissions accounted for 54 and 85 gCO_2e kg_{DM}^{-1}. Dried whole crops were produced by mowing the entire plant at the end of the ripening phase to obtain the maximum amount of industrial hemp biomass. Thus, the overall cumulative energy demand and environmental inputs for this product amounted to 2.24 MJ and 131 gCO_2e per kg of DM produced for S1 and 4.03 MJ kg^{-1} and 239 gCO_2e kg^{-1} produced for S2. Large differences were observed in the results from the two experimental fields, although the amounts and types of cultivation inputs were analogous for both sites. These variations were mainly attributed to the low production yields of S2.

Seed processing plant subsystem

After harvesting, the industrial hemp seeds were transported to the processing plant to produce nonfood hemp oil. The industrial hemp seed processing plant subsystem required a considerable amount of energy, which accounted for approximately 2.33 MJ of primary energy and a release of 73 g of CO_2e, with both of these numbers being expressed per kg of seed DM. Seed processing by rotary sieves and using an expeller screw press to extract the oil and obtain the cake byproduct was the most affected activity, which accounted for approximately 75% of the total primary energy requirements and emissions.

ADP subsystem

The subsystem associated with the ADP was involved in the HSC1 and HSC4 scenarios, which used residual industrial hemp straw and fresh industrial hemp biomass as feedstocks, respectively. The organic DM content and specific methane yields of these feedstocks affected the amounts of methane that were produced from the ADP and consequently, the energy generated. The total electricity production from the CHP unit was 4,582 and 2,291 kWh per fresh industrial hemp biomass for S1 and S2, respectively, while the residual industrial hemp straw generated approximately 1,139 and 592 kWh for S1 and S2, respectively. Specifically, the electricity yields were 0.73 and 0.27 kWh kg_{DM}^{-1} for the fresh industrial hemp biomass and residual industrial hemp straw, respectively. The large amount of thermal energy produced was managed to maintain the optimal thermal conditions (mesophilic) of the

Table 2
Assessed inputs of industrial hemp cultivation for each designed scenario and for each site.

Cultivation sites	S1	S2
Level of heavy metal contamination	Low contaminated soil	High contaminated soil
Cultivation INPUT		
Fertilizers (kg N ha^{-1})	60	60
Seeds (kg ha^{-1})	40	40
Irrigation water (m^3 ha^{-1})	4500	4000
Plastics (kg ha^{-1})	9	6
Fuel and Machinery INPUT		
Soil preparation Scenarios HSC1-2–3-4	Plowing (chisel plow)	Plowing (chisel plow)
Tractor power (kW)	67	67
Working time (h ha^{-1})	2.0	1.8
Diesel consumption (kg ha^{-1})	32	28
Soil preparation Scenarios HSC1-2–3-4	Harrowing	Harrowing
Tractor power (kW)	67	67
Working time (h ha^{-1})	1	1
Diesel consumption (kg ha^{-1})	13	13
Soil preparation Scenarios HSC1-2–3-4	Sowing	Sowing
Tractor power (kW)	67	67
Working time (h ha^{-1})	1	1
Diesel consumption (kg ha^{-1})	10	10
Soil preparation Scenarios HSC1-2–3-4	Rolling	Rolling
Tractor power (kW)	67	67
Working time (h ha^{-1})	0.33	0.33
Diesel consumption (kg ha^{-1})	3.6	3.6
Crop management Scenarios HSC1-2–3-4	Fertilization	Fertilization
Tractor power (kW)	67	67
Working time (h ha^{-1})	0.33	0.33
Diesel consumption (kg ha^{-1})	4.4	4.4
Harvesting activity Scenario HSC3	Mowing	Mowing
Tractor power (kW)	67	67
Working time (h ha^{-1})	1.2	1.1
Diesel consumption (kg ha^{-1})	14	12
Harvesting activity Scenarios HSC1-2	Harvesting	Harvesting
Harvester power (kW)	200	200
Working time (h ha^{-1})	1.7	1.5
Diesel consumption (kg ha^{-1})	25	20
Harvesting activity Scenarios HSC1-2–3	Straw raking	Straw raking
Tractor power (kW)	67	67
Working time (h ha^{-1})	0.65	0.55
Diesel consumption (kg ha^{-1})	6.5	6
Harvesting activity Scenarios HSC1-2–3	Straw bailing	Straw bailing
Tractor power (kW)	67	67
Working time (h ha^{-1})	0.45	0.33
Diesel consumption (kg ha^{-1})	9	7
Harvesting activity Scenarios HSC1-2–3	Bale loading	Bale loading
Tractor power (kW)	67	67
Working time (h ha^{-1})	0.5	0.3
Diesel consumption (kg ha^{-1})	9	7
Harvesting activity Scenario HSC4	Chopping	Chopping
Harvester power (kW)	488	488
Working time (h ha^{-1})	1.7	1.5
Diesel consumption (kg ha^{-1})	35	30
Harvesting activity Scenario HSC4	Biomass loading	Biomass loading
Tractor power (kW)	170	170
Working time (h ha^{-1})	1.7	1.5
Diesel consumption (kg ha^{-1})	18	15
Total diesel consumption at field		
Fuel consumption in Scenarios HSC1-2 (kg ha^{-1})	113	99
Fuel consumption in Scenario HSC3 (kg ha^{-1})	102	91
Fuel consumption in Scenario HSC4 (kg ha^{-1})	116	104

anaerobic reactor and to dewater the digestate, while the surplus heat that was produced from the CHP unit was assumed to be released into the atmosphere. The total renewable electricity that was produced from the ADP was used to replace the national electricity mix, which would avoid the exploitation of 6.25 and 2.38 MJ kg_{DM}^{-1} of primary energy per unit of fresh biomass and residual straw, respectively. Additionally, the energy valorization of the contaminated feedstock in the ADP enabled the avoidance of 191 and 74 g CO_2e kg_{DM}^{-1} of emissions from the industrial hemp products.

BFPP subsystem

The last subsystem in the overall designed scenarios (HSC1-2–3-4) involves the incineration of feedstocks in a BFPP for electricity production. The energy valorization of these feedstocks enabled the generation of 1,489 and 4,147 kWh of electricity. The total renewable electricity that was produced from the combustion of the contaminated biomass was assumed to replace the national electricity mix and avoided the exploitation of natural resources that corresponded to 8.63 and 9.07 MJ kg_{DM}^{-1} for the residual straw and dried whole crop, respectively, while the combustion of the dewatered digestates (from the residual straw and silage) showed lower production yields, which accounted for 4.18 and 4.58 MJ kg_{DM}^{-1}, respectively. The energy valorization of the contaminated biomass allowed us to avoid considerable amounts of carbon emissions and accounted for 246 and 258 g of CO_2e per functional unit with respect to the residual straw and dried whole crop, respectively, while the dewatered digestate feedstocks accounted for 119 and 130 g of CO_2e kg_{DM}^{-1}. As shown in Fig. 5, the avoided primary energy and CO_2e emissions were considerably lower (approximately 50%) in the dewatered digestate feedstocks since the carbon content of the digestate masses was partially exploited during the AD treatments.

HM-contaminated industrial hemp supply chain

The results of the industrial hemp supply chain scenarios are summarized per system, where the primary energy requirements and CO_2e emissions of each subsystem are shown as positive values, while the primary energy saved, CO_2e emissions avoided and industrial hemp carbon sequestration are shown as negative values (Table 3).

The results that were obtained from scenario HSC1, where the industrial hemp cultivation and harvest inputs represent the most energy and environmental affecting subsystem, accounted for approximately 64% of the total impacts, which are expressed as weighted averages among the harvested products and field sites, while a minor proportion of the impact was attributed to transportation activities (approximately 6%).

The energy and environmental benefits that were obtained through the energy valorization of the contaminated biomass, both from the AD process (2.38 MJ kg_{DM}^{-1} and 74 g CO_2e kg_{DM}^{-1}) and final combustion of the dewatered digestate (4.18 MJ kg_{DM}^{-1} and 119 g CO_2e kg_{DM}^{-1}), were considerable. The HSC1 scenario allowed us to save, on average, between the experimental fields, approximately 5.15 MJ kg_{DM}^{-1} of energy and to avoid the emission of 110 g CO_2e kg_{DM}^{-1}.

The HSC2 scenario was designed analogously to scenario HSC1 except for the ADP subsystem. Although the cumulative energy demand and environmental impacts of the subsystems were similar to those obtained in scenario HSC1, the current industrial hemp supply chain allowed us to obtain, on average, between the experimental fields, primary energy savings of approximately 7.25 MJ kg_{DM}^{-1} and avoided the emission of 164 g of CO_2e kg_{DM}^{-1}.

The designed HSC3 scenario represents an industrial hemp-contaminated supply chain with fewer subsystems. The field subsystem impacts showed the highest values (on average 3.14 MJ kg_{DM}^{-1} and 185 g CO_2e kg_{DM}^{-1}), while transportation activities had a limited impact on the supply chain (approximately 6%). The total primary energy saved, which was expressed as the average of the experimental fields,

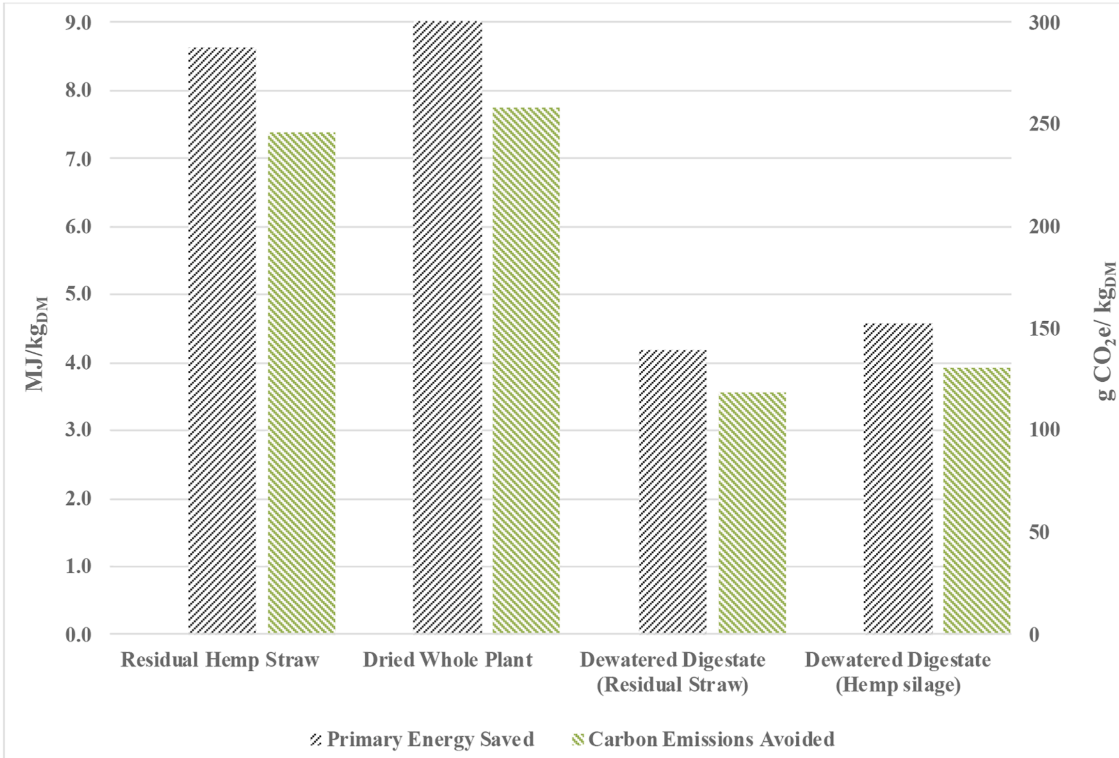

Fig. 5. Primary energy saved and CO_2 emissions avoided for the four compared industrial hemp products incinerated at the BFPP.

Table 3
Overall outcomes for the industrial hemp supply chain scenarios. Primary energy saved and carbon emissions avoided, expressed as averages between the experimental sites.

Items	HSC1		HSC2		HSC3		HSC4	
	CED (MJ kg_{DM}^{-1})	Climate Change ($gCO_2e\ kg_{DM}^{-1}$)	CED (MJ kg_{DM}^{-1})	Climate Change ($gCO_2e\ kg_{DM}^{-1}$)	CED (MJ kg_{DM}^{-1})	Climate Change ($gCO_2e\ kg_{DM}^{-1}$)	CED (MJ kg_{DM}^{-1})	Climate Change ($gCO_2e\ kg_{DM}^{-1}$)
Field								
Industrial hemp seeds	25.33	1514.44	25.33	1514.44				
Industrial hemp straw bales	1.19	69.31	1.19	69.31				
Dried whole crop					3.14	185.12		
Fresh hemp biomass (for silage)							2.78	168.20
Transportation								
FROM field TO seed processing plant	0.17	10.37	0.17	10.37				
FROM field TO anaerobic digestion plant	0.07	4.10					0.08	5.49
FROM field TO biomass-fired power plant			0.20	12.29	0.20	12.29		
Seeds Processing Plant								
Seeds processing	2.33	72.89	2.33	72.89				
Anaerobic Digestion Plant								
Feedstock valorization (biogas)	−2.38	−74.01					−6.25	−190.59
Transport								
FROM anaerobic digestion plant TO biomass-fired power plant	0.16	10.00					0.16	10.00
Biomass-Fired Power Plant								
Feedstock valorization (electricity)	−4.18	−119.03	−8.63	−245.63	−9.07	−258.07	−4.58	−130.45
TOTAL IMPACTS	**−5.15**	**−109.63**	**−7.25**	**−164.03**	**−5.74**	**−60.66**	**−7.82**	**−137.35**

accounted for 5.74 MJ kg_{DM}^{-1}, while the avoided emissions corresponded to 61 g of $CO_2e\ kg_{DM}^{-1}$.

In the HSC4 scenario, the fresh industrial hemp plants were harvested after the complete flowering stage (by using a forage harvester) and were subsequently ensiled at the ADP to allow better storage of the feedstock. After the anaerobic fermentation of the silage, the biogas obtained was converted into electricity (which replaced the national electricity mix), and the dewatered digestate was delivered to the BFPP for additional energy generation (which replaced the national electricity mix).

This scenario showed that the cumulative energy demand and environmental impacts of the field subsystem accounted for, on average, 2.78 MJ kg_{DM}^{-1} and 168 g of $CO_2e\ kg_{DM}^{-1}$, while the transportation activities represented approximately 9.5% of the total impacts. The energy valorization of the industrial hemp-contaminated feedstock throughout anaerobic fermentation and later combustion in the BFPP provided 6.25 and 4.58 MJ kg_{DM}^{-1} of primary energy and avoided 191 and 130 g CO_2e kg_{DM}^{-1} of emissions, respectively. Overall, the designed Scenario HSC4 allowed energy savings, on average, between the two fields of approximately 7.82 MJ kg_{DM}^{-1} and avoided the emission of 137 g of CO_2e kg_{DM}^{-1}.

The results of the Monte Carlo simulations for the 4 designed industrial hemp supply chain scenarios demonstrated that the outcomes were robust and emphasized the energy and environmental benefits of using HM-contaminated biomass as an energy resource (Fig. 6).

The scenarios that enabled us to save greater amounts of energy were HSC4 and HSC2, which accounted for 36.8 ± 4.2 and 25.3 ± 2.6 GJ of primary energy per cultivated hectare, respectively. The environmental performance of HSC4 and HSC2 ranged from 242 ± 77 and 641 ± 102 kg of CO_2e ha^{-1}, respectively. The cumulative energy demands and climate change values of scenarios HSC3 and HSC4 had the largest uncertainties and exhibited the highest deviations from the mean. Overall, when considering the uncertainties found in the Monte Carlo simulations, the obtained results allowed us to confirm the environmental benefits of producing bioenergy from contaminated biomass.

Discussion

Cultivation system

When addressing the cumulative energy demand and environmental impacts of the field subsystem inputs, the overall scores were reported based on the amount of product that was harvested; thus, lower production yields had greater impacts. Moreover, the working times that were related to on-field activities were likely influenced by the biomass yields. In fact, the harvesting operations in S1 were slightly greater than the activities carried out in the S2 experimental field. Among the 4 harvested industrial hemp products, diesel fuel consumption and fertilizer were the inputs that were most affected in the field subsystem and together ranged from 73 and 82% of the total impacts, while machinery upstream manufacturing accounted for a minor proportion of the requirements (2–4%). These results were also confirmed by Zampori et al. [104] who found that fertilization is one of the main impacting processes in industrial hemp cultivation and harvest. Another energy and environmental aspect to emphasize is related to irrigation water. The cultivation of industrial hemp in Mediterranean climates, with low rainfall during the growing season, causes irrigation practices to be a fundamental requirement. This practice was included in this study, where the water sources at both experimental sites came from pressurized irrigation networks with negligible direct energy requirements. Moreover, as already stated, industrial hemp cultivation in southern Mediterranean conditions requires higher irrigation volumes, in contrast to northern environments, but has lower water requirements than other specialized crops, such as maize, that are commonly utilized in ADPs [26].

Industrial hemp seeds

The industrial hemp seed oils that were obtained from plants cultivated in contaminated soil can be used for nonfood products, such as oil, to revive fine furniture woods and in the biodiesel industry [19,35]. In fact, biodiesel is one of the most commonly accepted complementary fuels for diesel engines, where in recent years, the cost and competition with the food sector have been decreased by using nonedible feedstock [82]. Another application of nonedible oil has been proven by Quiles-Carrillo et al. [76], who discussed the use of maleinized industrial hemp seed oil to reduce the intrinsic brittleness of polylactide materials without compromising their mechanical resistance and to construct toughened biopolymer pieces, which can find interesting applications in, for instance, rigid packaging.

Challenges for the AD of contaminated biomass

The AD subsystem allowed us to explore the energy and environmental benefits of using the industrial hemp biomass that was obtained from contaminated soil for biogas production while avoiding secondary pollution. The digestates were modeled to be dewatered by using the heat from the CHP unit and then incinerated in a BFPP for electricity production. This solution, because of the reduction in the biomass to be disposed of in authorized plants, enables us to reduce the disposal costs and to obtain energy from renewable sources. To the authors' knowledge, the use of industrial hemp as feedstock for ADP has been well discussed in the scientific literature [3,7,31,39,52,53]; in contrast, the use of HM-contaminated industrial hemp biomass as feedstock for ADPs is absent. A recent review indicated that industrial hemp biomass is a suitable crop for AD applications with high biogas production yields [7,40]. Plants that are obtained in the phytostabilization of trace element-contaminated soil may affect biomass biodegradability [12],

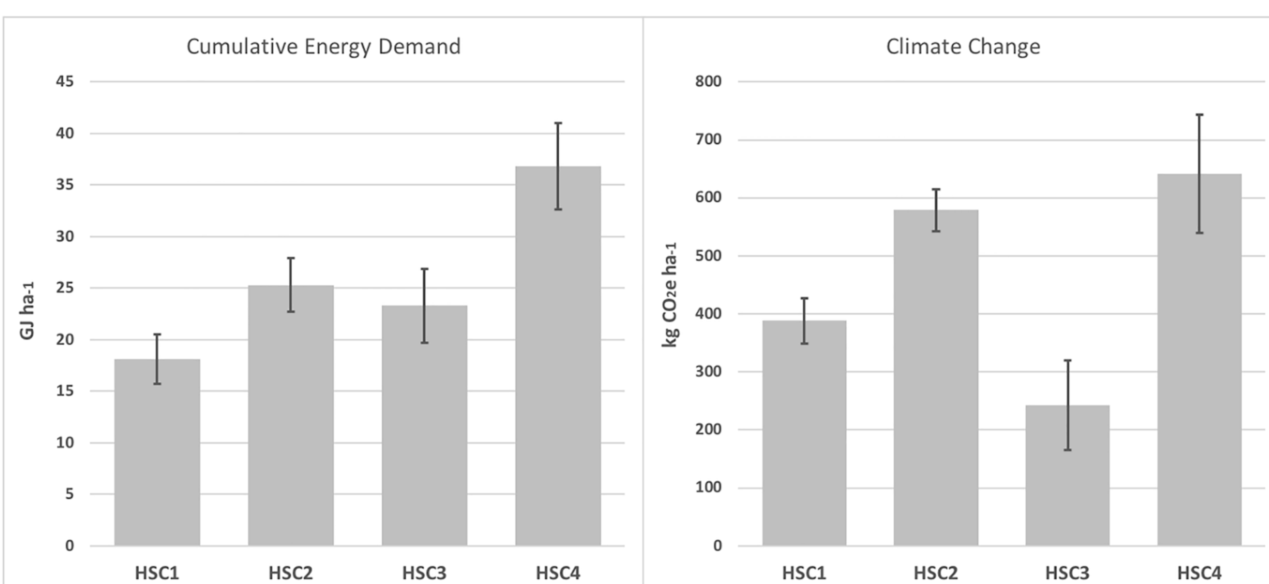

Fig. 6. Uncertainty analysis showing the LCIA results from Monte Carlo simulations for the industrial hemp supply chain scenarios.

while HMs affect the physiological and biotechnological environments in AD [1,106]. In fact, HMs interact with the microbial community and affect biogas production in AD processes, where trace HMs can promote biogas and methane production, while excessive HMs cause inhibition [22,38,67]. Lee et al. [55,56] demonstrated that the inhibition derived from HM-contaminated biomass was negligible, consequently, AD seems to be feasible for the disposal of HM-containing crop residues from phytoremediation sites [15]. However, the release characteristics and fates of HMs should be carefully considered to predict the stability of the AD process for HM-containing biomass [57].

Energy generation from contaminated plant residues

Regarding BFPPs, greater energy and environmental benefits might be achieved by using the waste heat that is generated by these plants. As reported by BEN [11], most of the heat derived from cogeneration plants is used in the same facilities, while a minor proportion (approximately 30%) is used in district heating networks to provide heating services to the domestic sector. Instead of dispersing the waste heat that is generated by thermoelectric power plants into the atmosphere, these plants might convey this heat for useful consumption, which would thus avoid burning fossil fuels that would otherwise be necessary to be consumed to provide the same heating service.

The disposal of biomass ash represents a point of debate in environmental studies [51,85]. The ash yields from biomass combustion range from 0.4 to 6% [73,90,91,97], and the ash compositions vary depending on the nature of the incinerated biomass [10,58]. For this reason, it is important to individually characterize each type of biomass ash prior to finding an appropriate utilization approach [47]. Biomass ash disposal has been found to be an influencing factor in the bioenergy and biowaste supply chain [61,71], while other studies have found that the contributions of the final disposal of biomass ash were not significant or were excluded from the study boundaries [16,34]. Biomass ash is free of nitrogen and contains large amounts of micro- and macronutrients that are highly suitable for mineral soil amendments [6,13,37,70,80], the biological reclamation of degraded areas [62] and dewatering sewage sludge [101]. In addition, a recent review by Cui et al. [20] emphasized that the incineration of contaminated biomass in modern incineration systems represents a technologically and economically feasible approach for treating hyperaccumulator plants, where ash residues could be pretreated and employed to produce construction materials and high-density glass-ceramics [28,81]. Modern incineration systems could employ environmentally sound technologies that would perform better than pyrolysis and gasification-melting plants because of several benefits of flue gas cleaning, ash recycling, and the combined heat and power cycle [29]. Moreover, these authors found that the efficient management of metals and bottom ash may decrease the volumes of waste landfills and reduce the consumption of raw materials.

Finally, these results identify the great potential of using contaminated areas for bioenergy production while minimizing the exploitation of natural resources and avoiding pollutant emissions into the environment. As suggested by Pulighe et al. [75], the cultivation of marginal lands for bioenergy production provides ample opportunities to conduct successful feedstock production in unmanaged areas. Currently, HM-contaminated soils are mostly unproductive and require expensive and long-term remediation programs to be turned into productive areas [21,48,64].

Conclusion

The LCA methodology was used to evaluate the cumulative energy demand and environmental impacts of using industrial hemp for phytoremediation in HM-contaminated soils under 4 different energy valorization scenarios. The results emphasized the sustainability of reclaiming contaminated soils when the contaminated biomass was valorized as an energy resource, and the main findings were as follows.

1) Industrial hemp cultivation was the subsystem with the greatest cumulative energy demand and environmental impacts along the entire supply chain, where diesel fuel and fertilizers are used for industrial hemp growth. Biomass yields had a significant effect on the environmental indicators, where higher levels of industrial hemp biomass production were linked to greater energy and environmental benefits.
2) The AD of biomass represents a valuable process to obtain bioenergy from contaminated feedstocks. However, local legislation in terms of the treatment and disposal of contaminated materials might represent an important concern for this technology. This study underlined that dewatering the contaminated digestate, using the surplus heat from the CHP unit, and then incinerating the dewatered digestate at a BFPP enabled the generation of remarkable amounts of renewable energy and consequently avoided pollutant emissions into the environment. Greater energy and environmental benefits might be achieved by exploiting the waste heat from BFPPs in district heating networks to provide heating services to the domestic sector.
3) Among the 4 designed industrial hemp supply chain scenarios, the systems that were associated with saving greater amounts of energy included AD and/or incineration of the contaminated biomass, with total primary energy savings that ranged from 18.1 to 36.8 GJ ha^{-1}, while the environmental performance ranged between 242 and 641 kg of avoided CO_2e emissions per reclaimed hectare. These results were confirmed by Monte Carlo simulations and indicated the great potential of using contaminated areas for bioenergy production while decreasing the exploitation of natural resources and avoiding GHG emissions into the environment. The uncertainty analysis enabled a better and more detailed interpretation of the impact assessment results and improved the robustness of the study. Moreover, phytoremediation practices and the energy valorization of contaminated biomass are recommended to change unproductive HM-polluted soils into exploitable and productive areas.
4) Finally, this work evaluated the technical, energy and environmental aspects that are related to the energy valorization of contaminated biomass and identified the major issues and opportunities, where policy uncertainties represent one of the major limitations. European and national standards are continuously evolving, which causes this field of study to be difficult to investigate. Furthermore, without a clear regulatory framework, it is challenging to plan or invest in this sector with acceptable risk rates.

Data availability

Supplementary data can be found in the co-submitted Data in Brief article, while an Excel dataset is hosted in the Mendeley Data repository (https://data.mendeley.com/datasets/p4btx7kptd/1; DOI: https://doi.org/10.17632/p4btx7kptd.1).

CRediT authorship contribution statement

Giuseppe Todde: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Gianluca Carboni:** Conceptualization, Resources, Supervision, Writing – review & editing. **Serena Marras:** Conceptualization, Writing – review & editing. **Maria Caria:** Conceptualization, Formal analysis, Writing – review & editing, Supervision. **Costantino Sirca:** Conceptualization, Resources, Writing – review & editing, Supervision.

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.

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