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LCA FOR AGRICULTURE

Life cycle assessment of hemp-based milk alternative production in Lower Saxony, Germany, based on a material flow analysis of a pilot scale

Jannatul Ferdouse[1] · Beatriz Q. Silva[1,2] · Marie-Christin Baune[1] · Nino Terjung[1] · Sergiy Smetana[1,3]

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Abstract

Purpose Recently, demand for plant-based milk products (PBMP) has increased for multiple reasons, such as the rapid population growth expected to reach 9.7 billion by 2050, health concerns such as lactose intolerance, nutritional aspects, ethical reasons, and environmental concerns. This leads to increased demand for food and competition for natural resources. Hemp-based milk is an emerging dairy alternative, and stakeholders in the supply chain are becoming increasingly interested in learning about the environmental effects of its production. This article aims for a comparative life cycle assessment of hemp-based and bovine milk with fat and protein correction to account for the differences in macronutrient content.

Methods The cradle-to-factory gate LCA relied on experimental cultivation and milk production in Lower Saxony, Germany. Inventory was based on primary data from fields and the pilot plant of DIL e. V. and on literature and ecoinvent database to develop a life cycle assessment (LCA) model. The LCA was performed using Simapro 9.3 software and IMPACT 2002+ impact assessment method. The life cycle stages include cultivation, harvesting, and milk production. The study compared hemp-based milk to bovine milk based on 1 kg fat and protein-corrected milk (FPCM) as a functional unit (FU). Co-products are taken into consideration using mass-economic allocation.

Results The results showed that hemp cultivation accounted for the highest impact (99%) in the production chain of hemp milk production. The GWP of 1 kg of FPCM hemp-based milk is 0.42 kg CO_2 eq. The energy consumption for 1 kg of FPCM hemp-based milk is 4.73 MJ (12.26% lower than bovine milk). The other main factors impacting hemp-based milk production were terrestrial ecotoxicity (6.444E2 kg TEG soil) and aquatic ecotoxicity (2.458E2 kg TEG water). Hemp fiber was the co-product with 40% of the allocated impacts. The results are sensitive to the changes in fat-protein contents, functional unit, and system boundaries. The results demonstrated that the impacts of hemp milk production were within the range indicated for other PBMP production and 51.7% lower than bovine milk production in terms of GWP. This range primarily stems from field emissions, fertilizer application, and machinery usage during cultivation and harvest.

Conclusion The results of the comparisons of bovine milk and hemp-based milk were dependable on the FU. The hemp-based milk has the potential to be a more sustainable alternative to bovine milk due to considerably lower impacts in impact categories—land occupation (99% lower than bovine milk), global warming (52% lower than bovine milk), and ionizing radiation (23% lower than bovine milk). It is primarily due to less use of agricultural machinery, less land requirement, and lower NH_3 emissions than bovine milk in various stages of milk production.

Keywords Life cycle assessment · Impact assessment · Hemp milk alternative · Plant-based milk alternative · Vegan milk

1 Introduction

By 2050, the world population will reach 9.7 billion people, and the food sector is facing a challenging future (Heines et al. 2022). To supply the population with the same amount of food, food production must increase by 70% (Heines et al. 2022), which means a higher need for inputs (energy, water, and others), increased competition for the limited available natural resources, and increased impacts (Fanzo et al. 2022). Overexploitation of natural resources leads to consumers' and stakeholders' growing awareness of the environmental impacts of food products (Kyttä et al. 2019) and demand for more sustainable alternatives. For example, the animal industry (production of meat, milk, and

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derivates) has one of the most significant environmental footprints (Geburt et al. 2022).

Several studies demonstrate that livestock and industrial milk production account for severe environmental impacts (Grant and Hicks 2018; Paul et al. 2019; Vanga and Raghavan 2017). Livestock comprises about 11.1–19.6% of the total GHG emissions (Xu et al. 2021). Moreover, dairy cattle alone generate approximately 21 gigatons of CO_2 eq yearly globally (FAO 2023), while animal-based protein sources such as milk and meat have a high environmental impact (Carvalho et al. 2021; Smetana et al. 2021, 2023). Consumer habits are changing towards alternative products such as algae, legumes, cultured meat, insects, and plant-based milk (Fanzo et al. 2022). There are multiple reasons for this change in consumer habits, such as changes in diets, nutritional benefits of plant-based alternatives, environmental concerns, ethical concerns, and health concerns (Scholz-Ahrens et al. 2019). One of the categories of consumers' growing interest is plant-based milk products (PBMP). PBMPs are emulsions that combine plant ingredients with water to replicate the taste and consistency of cow milk (Aydar et al. 2020; McClements et al. 2019). Due to their well-known taste, positive health effects, and ethical and environmental awareness, PBMPs quickly achieved market popularity, especially among millennials (Pointke et al. 2022). In the USA, they account for 13% of all milk sales, and 74% of customers in Germany prefer them over cow milk (Proctor 2022). For the average person, dairy products provide their nutritional needs (Chalupa-Krebzdak et al. 2018; Singhal et al. 2017) and offer beneficial and necessary elements like calcium, phosphorus, vitamin A, vitamin D, B12, potassium, zinc, lipids, and proteins (Silva and Smetana 2022). Consumers prefer plant-based milk over health issues, including lactose intolerance and milk allergies, low water requirements, low GHG emissions, and animal welfare concerns (Geburt et al. 2022; Pointke et al. 2022). Nutritionally, PBMP also offers nutritional advantages, as outlined in Table 1. The nutritional profiles of plant-based alternatives and bovine milk can differ considerably (Vanga and Raghavan 2017). The nutritional profiles of these dairy alternatives greatly depend on the plant source and processing (McClements et al. 2019). After cow's milk, almond milk has the highest protein content, followed by soy, oat, and hemp milk (Vanga and Raghavan 2017). Plant-based beverages have a lower fat content than bovine milk. It also contains some fiber concentration, unlike bovine milk, which has no dietary fiber. However, due to added sugar in many plant-based beverages, they tend to have higher carbohydrates than bovine milk (Silva and Smetana 2022). Likewise, the growth of other PBMPs (e.g., soy milk, almond milk, coconut milk, cashew milk, rice milk), hemp-based milk alternative is also gathering interest due to nutritional, sustainable profile and increasing legalization of hemp crop cultivation (Nasrollahzadeh et al. 2022).

Industrial hemp (*Cannabis sativa*) is cultivated (Campiglia et al. 2020) for animal feed, paper, biodegradable plastics, the construction sector, or textile production (Campiglia et al. 2020; Van Eynde 2015). The seeds can be utilized for feed, oil, and milk production (Carus 2013). *C. sativa* is a fast-growing plant (harvestable biomass in 90–120 days) that requires low inputs of fertilizers and no pesticides (Sayner, 2022; Van Eynde 2015). It is also an economically valuable crop, cumulating $824 million in 2021, where the sales value of seeds was $23.7 million (Nseir 2022). Hemp cultivation has other environmental benefits, such as returning nutrients to the soil, sequestering more CO_2 than other plants, and mitigating soil desertification (Baraniecki et al. 2013). Consumers generally perceive hemp-based milk as an environmentally friendly alternative to bovine milk (Geburt et al. 2022; Sethi et al. 2016). But many PBMPs also have significant adverse environmental effects: soy farming can cause land use change (biodiversity loss) and environmental acidification, rice farming is known for high water usage and methane production, and almond growing results in zinc pollution and water use (Geburt et al. 2022; Grant and Hicks 2018). To our knowledge, there are many environmental studies and LCA studies on hemp fiber (Van Eynde 2015), hemp textile (Essel 2013) and leather (van der Werf and Turunen 2008), hemp seeds (Campiglia et al. 2020), hemp hurd (Morselli et al. 2021), or other uses of hemp (Zampori et al. 2013). Also, there are multiple studies on hemp cultivation (Dhondt and Muthu 2020; Baraniecki et al. 2013), stable hemp milk production (Wang et al. 2018), and properties of hemp milk (Nasrollahzadeh et al. 2022). These studies highlight the cultivation of hemp impact assessment, and some studies extend until the end of life. The most discussed environmental hotspots in the mentioned studies are global warming potential, terrestrial acidification, eutrophication, ecotoxicity, land use, and fossil resource scarcity or energy use. This is due to the field emissions such as NO_2, NH_3, and SO_2 emissions, nitrogen and phosphorus fertilization, land preparation, seed production, and additional stages of the production of the hemp product. Nevertheless, an environmental impact assessment on hemp-based milk production is currently unavailable; thus, it is necessary to comprehend the severity of the environmental impacts.

Life cycle assessment (LCA) is a widely used tool to examine the impact of a product, process, or service on the environment surrounding us (Geburt et al. 2022; Heusala et al. 2020). The LCA's objectives are either to (1) recommend a product over other alternatives based on that product's environmental effect or (2) specify the life stages that place the significant environmental impact (Schüler and Paulsen 2019; Kyttä et al. 2019). For an LCA of a chain

Table 1 Nutritional profile of bovine milk and other plant-based milk alternatives

Nutritional composition		Bovine milk	Soy milk	Almond milk	Oat milk	Rice milk	Coconut milk	Hemp milk
Carbohydrates (g/100 g)		12.8	4.64–8	4.30–8	24	9.41–12.70	3.75–9.41	0.31
Protein (g/100 g)		7.69	7	1–1.90	4	0.28–1.26	0.59–2.0	4
Fat (g/100 g)		7.98	3.1–4.3	2.5–3.60	2.5	0.97–1.11	4.12–6.0	8.16
Fiber (g/100 g)		0	0.64–0.74	1.15–1.35	2	0.30–0.65	5.30–5.98	0.6
Energy (g/100 g)		149	99.6	55–60	130	47–112	50–92	91.67
Minerals	Ca (mg)	109–140.83	0–385	14–325.29	7.8–300	0–330	0–495.0	12–125.0
	Fe (mg)	0.0295–0.080	0.39–2.60	0–1.80	0–0.60	0–0.96	0–4.01	0.15–6.58
	Mg (mg)	9–13.0	21–70.0	6–35.0	–	0.84–35	6.67–46.0	13.75
	P (mg)	85–121	49–150	9–120	–	36–90	2–256.35	54.84–63.98
	K (mg)	134.17–181	50.01–460	35–170	–	26.34–50	14.58–639.02	110–126.58
	Na (mg)	36–58	2.57–135	1–190	40–48	35.83–100.0	0–150.0	8.33–140.01
	Zn (mg)	0.12–0.53	0.56–0.94	0–0.94	–	0.13–0.94	0.02–0.94	–
Vitamins	Vit. A (μg)	0–59.0	0–77.14	0–180	37.5	0–150.0	0–60.0	0–37.50
	Vit. C. (mg)	0–1.50	0	0	0	0–0.50	0–1.0	0
	Vit. B1 (mg)	0.04–0.050	0.06–0.10	0	–	0.027	0.02–0.022	–
	Vit. B12 (μg)	0.375–0.80	0.3–1.0	0–77.14	–	0.63–1.0	0–1.25	–
	Vit. E (mg)	0.0625–0.080	4	1.2–19.20	–	0.13–3.0	–	–
	Vit. D (μg)	0.02–1.292	0.45–2.50	0.45–3.30	1.563	0–3.33	0–3.33	1.563
Source		Paul et al. (2019), Silva and Smetana (2022), Singhal et al. (2017)	Aydar et al. (2020), Chalupa-Krebzdak et al. (2018), Scholz-Ahrens et al. (2019), Silva and Smetana (2022)	Aydar et al. (2020), McClements et al. (2019), Silva and Smetana (2022)	Aydar et al. (2020), Sethi et al. (2016), Silva and Smetana (2022)	Chalupa-Krebzdak et al. (2018), Silva and Smetana (2022), Vanga and Raghavan (2017)	Rasika et al. (2021), Silva and Smetana (2022), Vanga and Raghavan (2017)	Silva and Smetana (2022), personal communica-tion with Baune M.-C. (DIL e.V., Germany, 2022)

of production of a given product, the authors consider the following stages: sourcing raw materials, producing and processing the product, transport, storage, use, and disposal of the waste. An LCA that includes all stages is known as "cradle-to-grave," from the procurement of materials to the end of life (disposal). "Cradle-to-gate" boundaries include the life cycle until the farm or factory gate while disregarding the consumer and disposal phases.

This research aims to perform a life cycle assessment (LCA) with available experimental data from *C. sativa* cultivation and hemp-based milk production to measure the environmental impacts of hemp-based milk as a possible milk alternative. We analyzed the available data to uncover the differences in environmental impact categories between bovine and hemp-based milk.

2 Methods

2.1 Life cycle assessment

The study relied on LCA method application as defined in ISO standards 14040 and 14044 (ISO 14044 2006; ISO 14040 2006). The framework's four phases comprised of goal and scope identification, life cycle inventory analysis, life cycle impact assessment, and interpretation according to similar studies (Dhondt and Muthu 2020; Recanati et al. 2018).

2.2 Goal and scope definition

This project aims to perform an attributional life cycle assessment (LCA) to calculate the environmental effects of hemp milk production from farm to factory gate to establish the environmental profile of hemp milk and compare with bovine milk on key aspects. We refined the most recent studies for quantitative data (seed yield, fiber production, pricing, etc.). Search terms like "industrial hemp," "Cannabis sativa," "industrial hemp, plant-based milk," "hempseed/hemp oil," "uses of hemp plant, uses of industrial hemp," and "hemp production" are a few examples of the terminology we used for our literature analysis.

The authors considered the inputs of energy and resources consequently in the model at every level, from hemp cultivation to pilot production in the production unit. Figure 1 summarizes the research and experimentation methodology the authors used throughout this research. The environmental effects of cow's milk and the potential of hemp-based milk as a dairy substitute in the PBMP category led to the research topic and purpose selection. According to the hypothesis, hemp-based milk will be more environmentally friendly than cow's milk, like most other PBMP. However, there have not been any LCA studies on hemp milk production. Therefore, the authors carried out preliminary literature research to gather and utilize information for experiments.

The LCA was performed using Simapro 9.3 software (PRé Consultants B.V., Amersfoort, The Netherlands), considering the life cycle stages of cultivation, harvesting, and milk processing. The authors chose to elaborate the discussion of LCA results on global warming potential, water depletion, land use, and energy consumption, as these categories are mostly discussed in the LCA studies of milk production. The authors collected data for the LCA of hemp milk from licensed agricultural farmers for hemp cultivation and pilot production at the German Institute for Food Technologies (DIL e. V.) in Germany. Information such as seed input, fertilization and manure slurry input volume, emissions from sowing and fertilization machinery, water input for milling, and electricity for milling are some of the examples of information collected as primary data. Missing LCA data on dairy milk production was collected from the available peer-reviewed scientific literature and the ecoinvent 3 database. Data on water uptake, transport of fertilization, output of crop material, and output of heavy metals are categorized in the section of missing data. The analyzed data was limited to 1 year, from May 2022 to October 2022, as a pilot production under the EU project—"Cooperative Hemp" in the region of Quakenbrück, Germany.

2.3 System boundaries and functional unit

The study's system boundary in Fig. 2 includes hemp farming, crop harvesting, hemp seed processing and transportation, hemp milk production, and facility operations (e.g., equipment, energy, etc.). Hemp farming was modeled using data from pilot-scale cultivation and modified from some seed-based PBMP LCA models (Amaducci and Gusovius 2010; Campiglia et al. 2020; Winans et al. 2019). We analyzed the production of hemp, the use of seeds, and production methods of hemp-based milk alternative, including milling, extraction, sieving, homogenization, and storage. The investigators in the pilot production process tested the hemp milk production method on a lab scale at DIL e. V., serving as a basis for the upcoming pilot industrial scale. The complete nutritional profile, external transportation, and use phase of hemp-based milk were excluded from the studies (cradle-to-factory gate boundary).

A standard comparable dairy farm includes a larger system boundary. The spatial limits of the farm, including the transportation to the dairy sector, make up the product system. The unit processes usually include breeding cattle, milking and cooling the milk, transport, concentrate, mineral salt, pasture, and corn silage production (Carvalho et al. 2021). For this study, we used data from ecoinvent 3 database and relied on system boundaries set there. They start

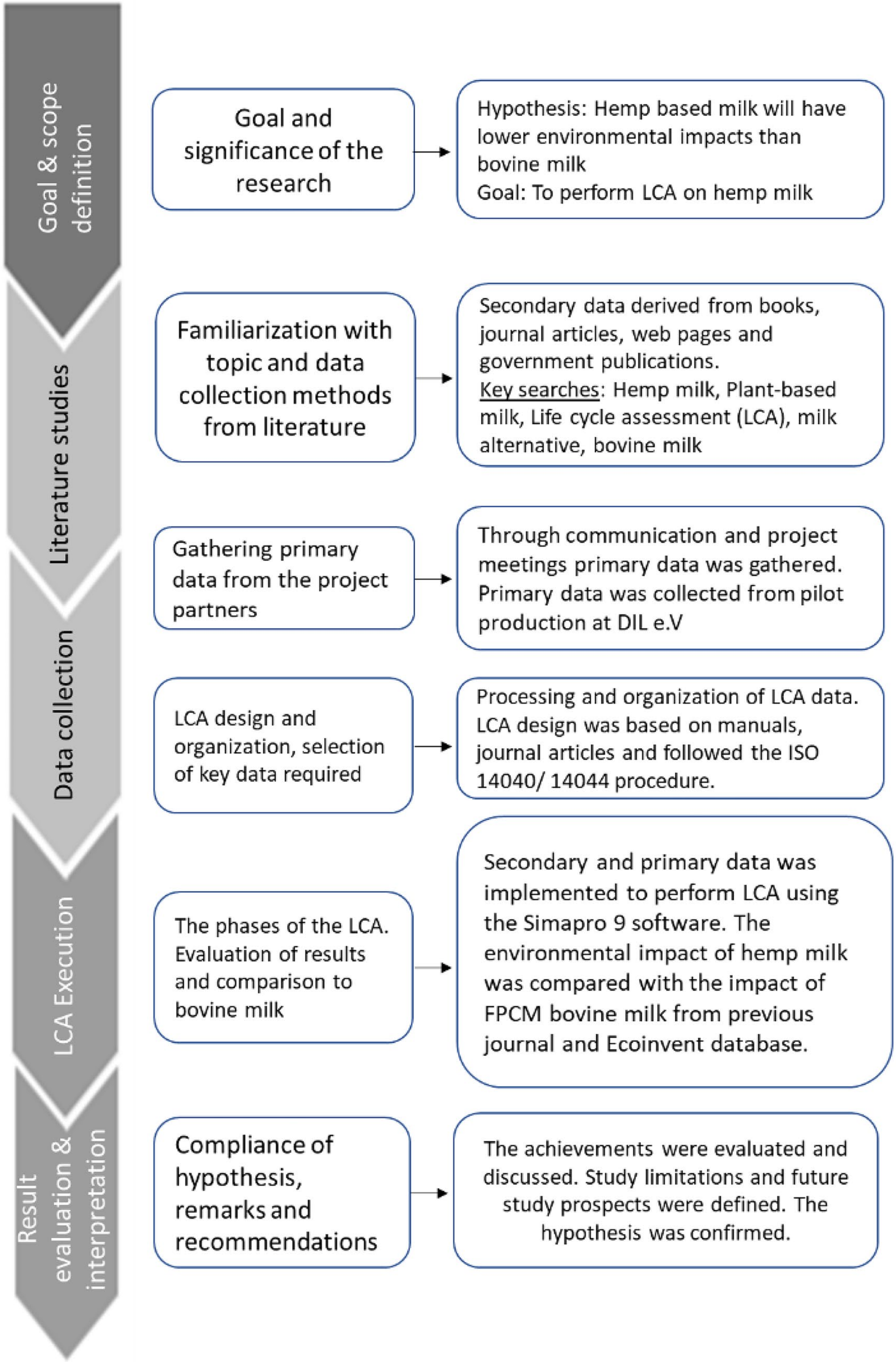

Fig. 1 Research approach employed in the study

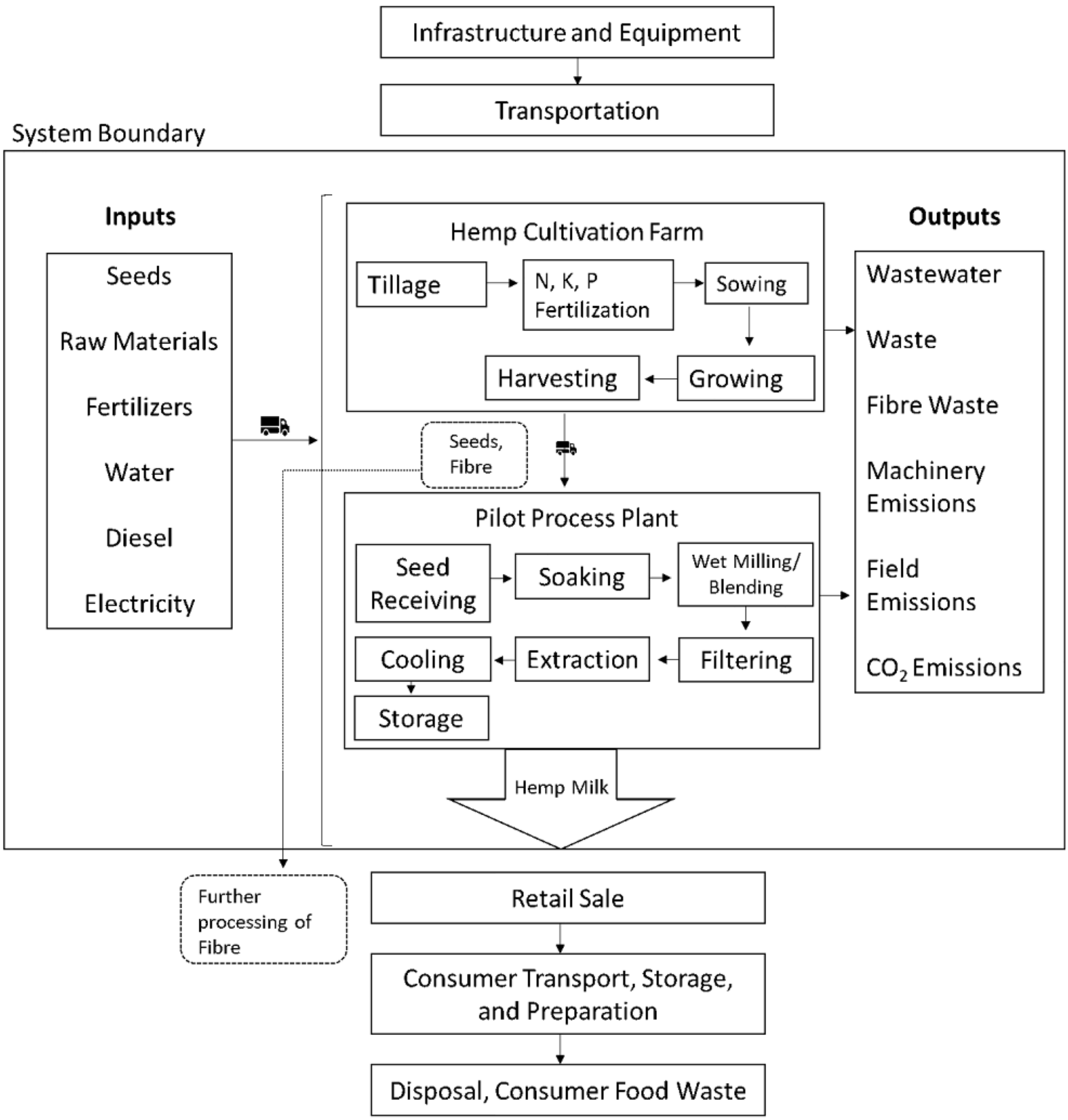

Fig. 2 System boundaries of hemp-based milk production

from the feed production, storage of feed materials, dairy herd housing, and end with provision of milk at farm, ready to deliver. The data used includes feed production and consumption, livestock management (including bedding, drinking water, milking equipment, cleaning products and water, ammonia and dinitrogen oxide emissions from housing, and methane emissions from enteric fermentation), manure management emissions, and energy and buildings (including electricity for dairying, cattle housing and milk parlor equipment and buildings, and gasoline for regular operations) necessary for the operation of a typical dairy farm.

In LCA studies, choosing a fair functional unit (FU) is crucial as it establishes the foundation for quantifying all inputs and outputs, allows for accurate interpretation of the results, and facilitates comparison of LCA results based on comparable functional performance of various processes, products, or systems (Bayram and Greiff 2023). According to ISO 14040/44, a FU is defined as the "quantified performance of a product system for use as a reference unit" (ISO 14040, 2006). It has to align with the study's objectives and parameters. In some research, the FU was measured in hectares (ha) (Rice et al. 2018), whereas other studies measured the FU in liters of milk, 1 ton of milk, 1 kg of milk, the protein content, energy content, and other units (Schau and Fet 2007). To avoid subjectivity when evaluating equivalence, the FU should include qualitative and quantitative aspects (Rice et al. 2018). Considering the points above, we took 1 kg of fat and protein-corrected milk (FPCM) as an FU for this study. This is an equalized nutrient unit to compare hemp-based milk with other plant-based milk or bovine milk with different nutrient content (Rice et al. 2018). Defining a fair FU is crucial in comparing dairy production and milk alternatives (Mancilla-Leytón et al. 2021; Rice et al. 2018; Schüler and Paulsen 2019). Using the FPCM formulation in Eq. 1, bovine milk is standardized to 4% fat and 3.3% true protein per kilogram as per previous studies (Rasika et al. 2021; Rice et al. 2018). An investigator can obtain FPCM of hemp milk by multiplying milk production with the fat-protein content of a specific farm's milk and the standard milk energy content (Tello et al. 2021). We calculated the FPCM considering the fat and protein percentages obtained at pilot-scale production at DIL e. V. provided in Table 1.

Equation 1 was used for FPCM calculation according to FAO (2010), Tello et al. (2021), and Yan et al. (2011).

$$kg\ FPCM = kg\ (milk\ yield) \times (0.337 + 0.116 \times Fat\ \% + 0.06 \times Protein\ \%) \quad (1)$$

As a result of calculations, 1 kg of FPCM (bovine milk) was equal to 0.953 kg of bovine milk. At the same time, the amount of 1 kg of FPCM (hemp milk) was equal to 1.523 kg of produced hemp milk. The FU of 1 kg FPCM was selected for the impact assessment and uncertainty analysis.

2.4 Life cycle inventory

The life cycle inventory (LCI) is the second stage of an LCA, outlined in Table 2, and it determines the quantity of all input and output flows within the system boundaries (ISO 2006).

2.5 Material flow of hemp-based milk production

Hemp-based milk follows a similar production process to most other PBMPs. The flow diagram in Fig. 3 represents the production system of hemp-based milk at the pilot scale. The pilot production farmers initially leveled and tilled to prepare the soil for crop production, tillage, as described in Caffrey and Veal (2013). Similar to the studies in Zampori et al. (2013), the farmers fertilized the field later with cattle slurry or nitrogen fertilizers before they sowed the seeds. The growth, harvest, and transport of the hemp seeds required inputs such as fuel, water, machinery, and fertilizer. The authors considered these inputs for the inventory analysis. The hemp seeds are transported to the pilot plant from the fields and dried before being steeped in deionized water. In a technique identical to that described by Wang et al. (2018), the investigations utilized hemp seeds for additional milk processing and the seeds are steeped in a solution of 1:3 deionized water at 4 °C for 16 h. For wet milling, the water is discharged, and a comparable amount is added. Wet milling is the mechanical breaking down of seeds with added water. The final product's parameters are the amount of additional water, milling temperature, pH, milling type, and feed rate (Aydar et al. 2020). The experiment employed a Kotthoff toothed rim dispenser for wet milling, and we used a clamp meter to assess the power input. A three-phase main supply powers the motor. Hence, we used the three-phase power formula to calculate the work. A work of 0.0036 kWh work is estimated to produce 1 kg of hemp-based milk. To remove the large particles, a mesh sieve was used to filtrate the slurry. The authors refrigerated the final product without adding further emulsifiers or heat processes, which might have affected the taste and flavor of the final product.

2.6 Co-product allocation

In this study, mass and economic allocation are used to achieve the accuracy of the allocation. Allocation was required as the hemp crop delivers fibers/straws and seeds. Due to the different market processes of these products, both mass and economic allocation were applied. The mass of seeds (M_s) from 1 ha was 1046 kg/ha, and its price ($€_s$) was estimated to be 690.9 €/ha (Alberta Agriculture and Forestry 2020; Sayner 2022). On the other side, the mass of fibers (M_f) from 1 ha was 645 kg/ha, and its price ($€_f$) was estimated to be 1039.9 €/ha (Nseir 2022). The allocation factor (AF) of both seeds and fiber was calculated to be 60 and 40%, respectively, according to a similar allocation LCA study of hemp cultivation (Zampori et al. 2013).

$$AF_{(Seeds)} = \frac{€_s M_s}{€_s M_s + €_f M_f} = 0.6 \quad (2)$$

$$AF_{(fiber)} = \frac{€_f M_f}{€_s M_s + €_f M_f} = 0.4 \quad (3)$$

It was assumed that the average market producer of relevant products (straw, seeds) would be impacted considering there was insufficient information about the future development of hemp-based products on the market. The price variance could lead to added uncertainty, so the prices were

Table 2 Life cycle inventory for the hemp-based milk production

Inputs	Source	Outputs	Source
Cultivation and harvest			
Water for growth, 120 m^3/ha	Zampori et al. (2013)	Seed output at farm, 1460 kg/ha	ecoinvent
CO_2 uptake in growth, 607 kg/ha	Van Eynde (2015)	Fiber output at farm, 645 kg/ha	ecoinvent
Seeds for sowing, 35 kg/ha	Primary	CO_2 emissions to the air, 22.45 kg/ha	ecoinvent
Manure slurry from cattle, 308.9 kg/ha	ecoinvent	Ammonia emissions to the air, 8.47 kg/ha	ecoinvent
Diammonium phosphate (NH_3), 22.81 kg/ha	ecoinvent	Nitrogen monoxide, 0.315 kg/ha	ecoinvent
Ammonium sulfate (NH_4) NPK, 8.87 kg/ha	ecoinvent	Nitrate emissions to water, 59.79 kg/ha	ecoinvent
PK compound, 9.991 kg/ha	ecoinvent	phosphorus emissions to water, 0.46 kg/ha	ecoinvent
Triple superphosphate, 3.10 kg/ha	ecoinvent	Cadmium emissions to water, 34.86 mg/ha	ecoinvent
Transport of manure, 114.9 tkm	ecoinvent	Cadmium emissions to soil, 1475 mg/ha	ecoinvent
Transport of materials, 34.46 tkm	ecoinvent	Chromium emissions to water, 20,760 mg/ha	ecoinvent
Field plowing, 73.13 kg/ha	Zampori et al. (2013)	Chromium emissions to soil, 149,200 mg/ha	ecoinvent
Fertilization machinery fuel, 9 l/ha	Primary	Copper emissions to water, 3236 mg/ha	ecoinvent
Sowing machinery fuel, 20 l/ha	Primary	Copper emissions to soil, 1507 mg/ha	ecoinvent
Harvesting machinery fuel, 193 kg/ha	Zampori et al. (2013)	Mercury emissions to water, 0.67 mg/ha	ecoinvent
		Mercury emissions to soil, 46.09 mg/ha	ecoinvent
		Nickel emissions to soil, 11,520 mg/ha	ecoinvent
		Lead emissions to soil, 10,780 mg/ha	ecoinvent
		Zinc emissions to soil, 423,200 mg/ha	ecoinvent
Milling and extraction			
Seeds for milling, 1460 kg/ha	ecoinvent	Milk yield after milling, 5548 kg	Primary
Water for soaking and milling, 8760 kg	Primary	Biowaste from milling and filtration, 292 kg/ha	Primary
Electricity for milling seeds, 20.44 kWh	Primary	Wastewater, 4380 kg	Primary
Internal transportation, 0.005 kWh	Smetana et al. (2019)		
Cool storage, 0.034 kWh	Smetana et al. (2019)		

The investigations did not include wastewater treatment. The wastewater was an intermediate flow that emerged from the discard of water after soaking the hemp seeds before wet milling

based on a transparent and open market. However, vulnerability to market fluctuations is a disadvantage for economic allocation. Therefore, it is advised to use average economic values in order to reduce this effect (Carvalho et al. 2021).

2.7 Life cycle impact assessment

After defining the goals and scope and inventory analysis, life cycle impact assessment (LCIA) is the third stage of the LCA. The data collected in the LCI are analyzed and computed in the LCIA stage. The elementary flows from LCI translate into impact categories, and the LCA practitioner can identify the potential contribution of each elementary flow to the environmental impacts. The LCIA was carried out in line with the chosen impact categories, combining effects using characterization models to provide aggregated category indicators. The study primarily used the IMPACT 2002+ methodology (Jolliet et al. 2003), which included the presentation of results in 15 midpoint impact categories, which were subsequently combined through a normalization and weighting procedure into four endpoint categories reflecting distance to the target: human health, ecosystem quality, resource use, and climate change. It also enabled the midpoint effects to be weighted and combined into an integrated single score, indicating the relative relevance of a defined impact. Besides this, the AWARE V1.05 was used to calculate one more important impact category, not included in IMAPCT 2002+: water depletion. The choice of LCIA depended on two key factors—(1) comparability with other studies (Henderson et al. 2023; Kyttä et al. 2019) and (2) the potential for integrated and disintegrated analysis with reasonably low uncertainty (Jolliet et al. 2003). The study used SimaPro v9 (PRé Consultants B.V., Amersfoort, The Netherlands) for the calculations. To determine the uncertainty of results, Monte Carlo simulations with 1000 runs were performed to establish whether the conclusions were reasonable.

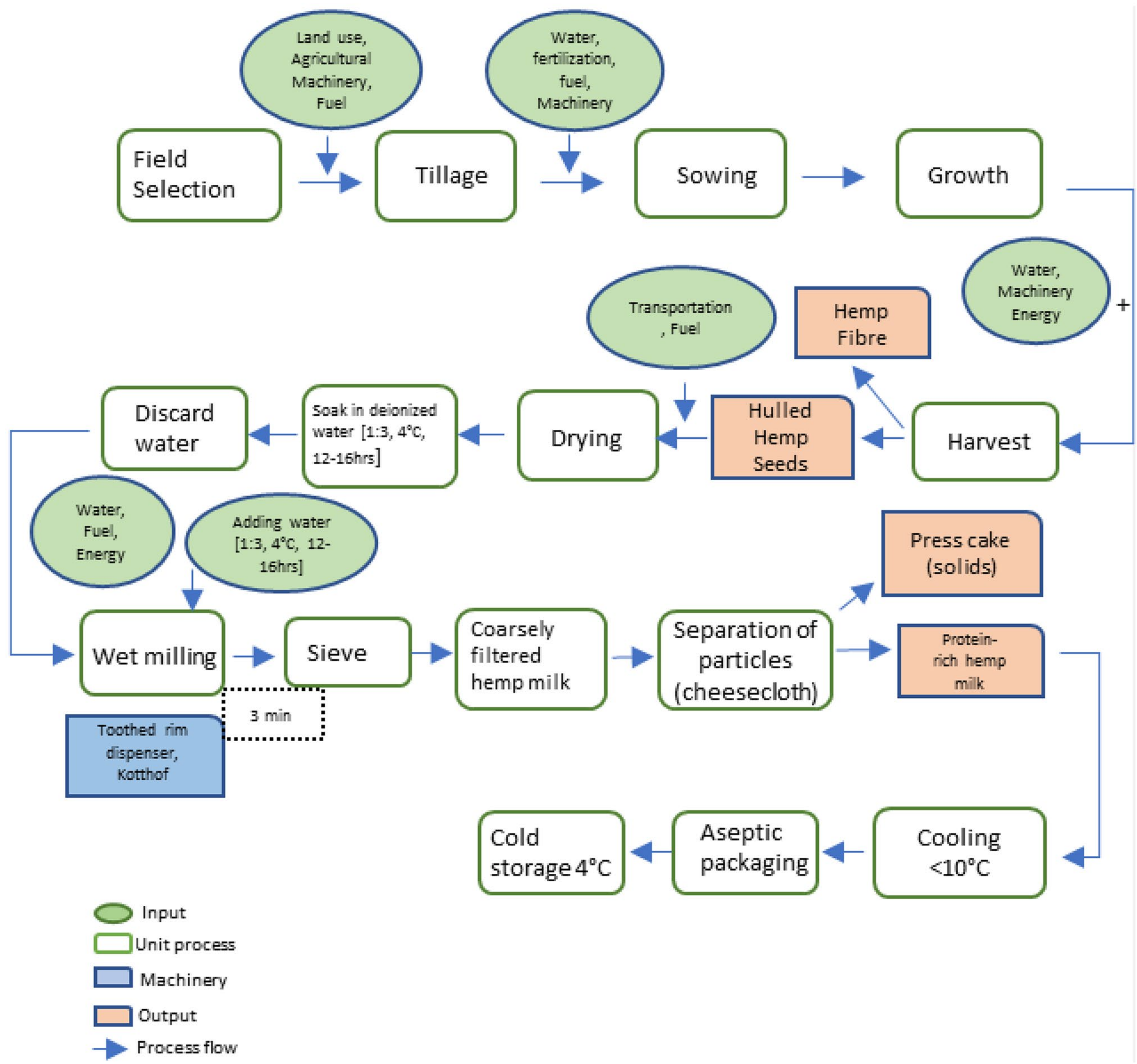

Fig. 3 Preliminary flowchart of hemp milk production

3 Results

The impact assessment results are presented in Table 3 both characterization of midpoint categories and single scores are presented for the established functional unit. The cultivation of hemp accounted for most of the impact, and 60% of the impact was allocated to seed production. For hemp milk production, the midpoint categories—aquatic ecotoxicity (2.458E2 kg TEG water) and terrestrial ecotoxicity (6.444E2 kg TEG soil)—achieved scores higher than bovine milk production. For bovine milk production, most midpoint categories had higher scores than hemp-based milk production, such as land occupation (11.9 m^2 organic arable land), global warming (0.87 kg CO_2 eq), and non-renewable energy (5.31 MJ primary) for 1 kg FPCM production. These values are mainly constituted by the impact released by the tillage, seeding the crops, and harvesting using fuel-intensive agriculture machinery.

The most significant impact category for hemp-based milk production is terrestrial ecotoxicity of 6.444E1 kg TEG soil compared to the score of −1.530E1 kg TEG soil for 1 kg FPCM bovine milk production. On the other hand, the most significant impact category in bovine milk production is land occupation, with 11.91 m^2 org. arable compared to only 0.05 m^2 org. arable in 1 kg FPCM hemp-based milk production. Production of 1 kg FPCM

Table 3 Life cycle impact assessment characterization results according to IMPACT 2002+ and AWARE V1.05 [water use impact category], comparison of bovine milk production to hemp-based milk production (FU—1 kg FPCM)

Impact category	Characterization		
	Unit	Hemp milk	Bovine milk
Carcinogens	kg C2H3Cl eq	1.222E−2	1.135E−2
Non-carcinogens	kg C2H3Cl eq	9.174E−2	1.328E−2
Respiratory inorganics	kg PM2.5 eq	6.364E−4	1.281E−3
Ionizing radiation	Bq C-14 eq	2.629E0	3.382E0
Ozone layer depletion	kg CFC-11 eq	2.156E−08	3.399E−08
Respiratory organics	kg C2H4 eq	4.931E−4	2.445E−4
Aquatic ecotoxicity	kg TEG water	2.458E2	6.163E1
Terrestrial ecotoxicity	kg TEG soil	6.444E2	− 1.530E1
Terrestrial acid/nutri	kg SO2 eq	9.344E−3	7.485E−2
Land occupation	m^2 org. arable	5.901E−2	1.191E1
Aquatic acidification	kg SO2 eq	2.349E−3	1.049E−2
Aquatic eutrophication	kg PO4 P-lim	8.677E−05	4.601E−4
Global warming	kg CO2 eq	4.173E−1	8.677E−1
Non-renewable energy	MJ primary	4.739E0	5.3189E0
Mineral extraction	MJ surplus	4.164E−2	2.285E−2
Water use	m^3	1.95E−1	6.64E−1
Single score	mPt	5.56E−1	1.204E0

hemp-based milk performed better in most other impact categories than bovine milk production. Some of those impact categories include global warming (41.68% for 1 kg FPCM hemp-based milk and 86.77% for 1 kg FPCM bovine milk), ionizing radiation (261.09% for 1 kg FPCM hemp-based milk and 338.22% for 1 kg bovine milk), terrestrial acidification (0.93% for 1 kg FPCM hemp-based milk and 7.49% for 1 kg FPCM bovine milk), and non-renewable energy (473% for 1 kg FPCM hemp-based milk and 531.89% for 1 kg FPCM bovine milk). Figure 4 shows the distribution of midpoint weighted impact categories of 1 kg FPCM hemp-based milk and bovine milk production and the single score of bovine milk and hemp milk production. Hemp-based milk also had a lower impact on the endpoint categories than bovine milk. In human health, hemp milk (0.104 DALY) accounted for 30% lesser impact than bovine milk (0.148 DALY). In the category of ecosystem quality, hemp milk (0.378 PDF·m^2·year) has a 60.47% lesser impact than bovine milk (0.958 PDF·m^2·year). Similarly, in the endpoint categories of climate change (0.42 kg CO_2 eq for hemp-based milk and 0.87 kg CO_2 eq for bovine milk) and resources (0.031 MJ for hemp-based milk and 0.038 MJ for bovine milk), hemp-based milk achieved scores 54.91 and 17.62% lower respectively than bovine milk.

The LCA results demonstrated that single impact assessment scores are 0.55 mPt for hemp-based milk and 1.20 mPt for bovine milk production. We calculated the uncertainty with 1000 Monte Carlo runs represented as error bars in Fig. 4 on the single score. Bovine milk has more significant uncertainty (+ 0.010, − 0.0105) than hemp-based milk (+ 2.11×10^{-5}, − 1.86×10^{-5}), which could result from the differing background data sources. The choice of FU and fat-protein content has been shown to affect the analysis according to similar studies (Mancilla-Leytón et al. 2021; Rice et al. 2018; Schüler and Paulsen 2019). For the endpoint impact category, 1 kg of FPCM bovine milk constituted 1.36×10^{-1} DALY (human health), 9.75×10^{-1} PDF*m^2·year (ecosystem quality), 0.87 kg CO_2 eq (climate change), and 3.51×10^{-2} MJ primary energy (resources). For 1 kg of FPCM hemp-based milk, the endpoint impact categories were 1.04×10^{-1} DALY (human health), 3.78×10^{-1} PDF*m^2·year (ecosystem quality), 0.42 kg CO_2 eq (climate change), and 3.14×10^{-2} MJ primary energy (resources).

4 Discussion

4.1 Midpoint categories

In evaluating the midway category impacts of the IMPACT 2002+ impact assessment technique, hemp production and cultivation were shown to be the primary contributors to environmental pollution across all categories. In the milling process, hemp seed milling was the most environmentally damaging in global warming and non-renewable energy. This could be from the bio-remediating potential of hemp, which removes heavy metals from fertilizer emissions. The transportation of the agricultural machinery, transportation of seeds, field cultivation, harvesting, and fertilizer contributed towards terrestrial ecotoxicity, terrestrial acid/nutri, and aquatic ecotoxicity as they emitted sulfur, nitrogen oxides, and particulate matter that led to soil acidification and health impacts (Heines et al. 2022).

4.1.1 Global warming potential

One of the main criteria used to assess a product's environmental performance is its GWP. In Europe, the average GWP of cow's milk ranges between 1 and 2 kg CO_2 eq (Tello et al. 2021). The global warming potential of hemp milk is 51.7% lower than hemp-based milk due to NH_3 emissions from enteric fermentation in dairy cows, in pasture production, grazing, and processing of milk and meat through various stages (Ho et al. 2016; Kyttä et al. 2019). The global warming category was defined mainly by the transportation of agricultural machinery, fertilizer application, harvest and internal transportation, and land occupation. Cultivation and harvesting of the crops and fertilization resulted in methane release at various stages of hemp seed production (Meyer

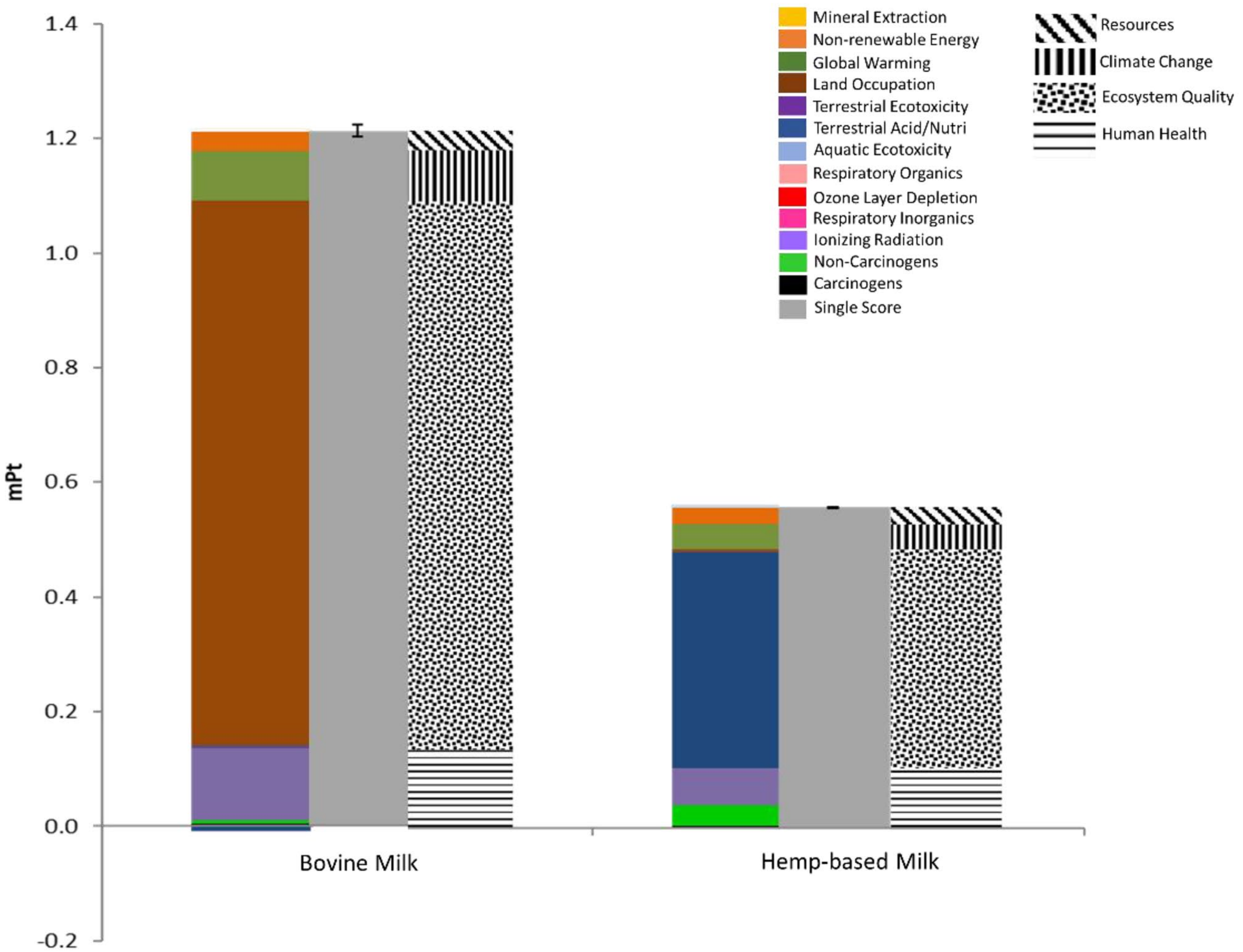

Fig. 4 Comparative environmental impacts of bovine milk and hemp-based milk alternative (FU: 1 kg FPCM). The first bar of each milk type demonstrates the midpoint categories, the second bar shows the single score and the uncertainty (with error bars) with 1000 Monte Carlo runs, and the third bar shows the damage categories (endpoints). Method: IMPACT 2002+V2.12, error bars are standard deviation with confidence interval of 95%. Production of 1 kg FPCM hemp-based milk has 54.17% lower impact than 1 kg FPCM bovine milk

and Theuvsen 2017). Due to the heterogeneity of data, which includes the functional unit, system boundaries, country of assessment, processing technology, and packing, comparisons among various studies can be made based only on key differences to reach a reasonable conclusion.

4.1.2 Land use

The land occupation for bovine milk production is much higher than hemp-based milk production, as dairy milk production involves extensive land use. The higher land occupation in bovine milk production could be explained by large-scale farming, which impacts the land occupation category by destroying virgin land and eliminating biodiversity for grazing and pasture production. Some studies suggest forage production for the dairy sector is associated with 63–66% of land use (Carvalho et al. 2021). The land use for hemp-based milk production was only 0.05 m^2 org. arable primarily due to the rapid growth rate produced in less land area (Dhondt and Muthu 2020).

4.1.3 Non-renewable energy

The bovine milk processing uses 7.9 MJ primary energy per kilogram of product, releasing more than 10 g of SO_2 and 1.9 g of PO_4 into the environment (Tello et al. 2021). The non-renewable energy in this study was 4.73 MJ primary for 1 kg FPCM hemp-based milk and 5.31 MJ primary for 1 kg FPCM bovine milk mainly due to various stages of transportation, fieldwork, harvesting, production of finished goods, seeds and field processing, harvesting and milling. The fuel production process required for various stages of hemp crop production uses low-voltage electricity emerging from non-sustainable sources like fossil fuels. In the case of hemp agriculture, the manufacture and use of diesel (47%) and N fertilizer production (39%) account for the majority of the energy usage (Van Der Werf 2004). The remaining contributors come from processes that make lesser contributions to energy use.

4.1.4 Water use

Water is a scarce resource, widely used in agriculture. Both hemp milk and bovine milk rely on the resource for the production. Water use potential is representing the potential use of water in relation the scarcity of this source in the different regions (Boulay et al. 2017). Hemp milk is also demonstrated to have water use footprint: 0.195 m^3 for the production of 1 kg of hemp milk versus 0.664 m^3 for the production of 1 kg bovine milk (FPCM). It is obvious that cows required more water in the production chain of milk.

4.2 Single scores

Compared to a similar scenario of bovine milk production, the hemp-based milk production scenario is more than twice as sustainable. Dairy milk production involves extensive resources in its system boundaries, requires inputs of fuel, energy, and resources, and requires rearing and maintenance of the dairy cows throughout their lifetime. The housing system of dairy cows plays a role due to the lack of optimal conditions, and other non-efficient systems lead to increased energy demand or higher environmental impacts. The single score impact results showed that this LCA study's uncertainty level was reasonably low. A low uncertainty suggests more dependable results as it explains how often the measurement will yield the same results. The single score was generated using IMPACT 2002+ following the guidelines in Simapro. The manufacture of various dairy alternatives from hemp, such as hemp-based cheese, and the necessity for background data enhancement for future consequential LCA modeling of hemp-based milk were both pointed out. More benchmark product modeling using first-class data should lead to better results.

Other emissions, such as nitrogen oxides and phosphorous, also occurred due to cattle or pig slurry manure application. Over 70% of the impact of standardized bovine milk comes from the feed dairy cattle consume, with 99% coming from raw milk production. Hemp-based milk has less influence on the environment, especially at endpoints related to climate change, resources, human health, respiratory organics and inorganics, ozone layer depletion, aquatic acidification, and aquatic eutrophication. Land use of hemp-based milk showed over 200 times lesser impact than bovine milk production. The impact of standardized bovine milk is 0.64 mPt greater than hemp-based milk. Hemp-based milk, however, posed a more significant strain on aquatic ecotoxicity, terrestrial ecotoxicity, carcinogens, and non-carcinogens. During the cultivation stage, heavy metal emissions, fertilizer production and usage, and water consumption contribute significantly to these numbers. A significant contribution related to carcinogenic and non-carcinogenic toxicity is from fertilizer production (39%), pesticide emissions (27%), and fertilizer emissions (19%) (Van Der Werf 2004). In general, hemp-based milk has a lesser impact than standardized bovine milk. This lower impact results from the standardization of the bovine milk manufacturing process and the disregard for heating and packaging. At the pilot-scale trials, the product developed contained 4% protein and 8.16% fat. Several studies show that choosing FU and fat-protein content affects the impact analysis (Mancilla-Leytón et al. 2021; Rice et al. 2018; Schüler and Paulsen 2019). Additional trials aiming to lower the fat content could affect the analysis, which could be said after further investigation.

The environmental benefits of cultivating hemp are suggested to be lower than many other plant-based milk-producing crops. For example, oat milk has the highest value of land usage among plant-based milks (0.66 m^2), followed by soy milk (0.66 m^2), almond milk (0.50 m^2), and rice milk (0.34 m^2) (Silva and Smetana 2022). In the sector of water consumption, production of almond milk (59–6100 L/L of milk) and cow milk (11.7–1030 L/L of milk) are the two sources with the highest water usage (Silva and Smetana 2022). According to Silva and Smetana (2022) and Winans et al. (2019), a significant portion of the effects on the production of almond milk come from the manufacturing of almonds. The manufacture of rice milk uses the most and the least energy (both renewable and non-renewable), consuming 1.04–47.60 MJ per liter of milk, whereas the production of almond and cow milk uses 1.53–36.90 MJ and 2.7–36.30 MJ, respectively (Silva and Smetana 2022). Some of the environmental impacts vary greatly such as land use for bovine milk production (0.64–55 m^2a crop eq), soy milk production (0.49–0.7 m^2a crop eq), water consumption of bovine milk production (0.17–7.66 m^3), energy consumption of bovine milk production (17.3–36.3 MJ), and energy consumption of rice milk production (1.04–47.60 MJ). This is mainly due to differences in system boundaries, emissions in respective country of studies, technological variance, source of energy production, farmers' knowledge, climatic fluctuations, rainfall and weather, and other factors (Clune et al. 2017; Ho et al. 2016). Van Der Werf (2004) suggests that the environmental impacts of cultivating hemp are lower than many other plant-based milk-producing crops. A detailed comparative study of hemp-based milk with other plant-based milk and bovine milk could clarify the impacts and suggest possible beneficial milk or milk alternatives for consumers. However, the industry must be conscious of its next steps to ensure the environmental benefits of PBMP or hemp-based milk.

4.3 Sensitivity analysis

To evaluate the study's completeness and verify the changes caused by a parameter, the authors carried out a sensitivity analysis to assess the potential magnitude of environmental impact reduction. Figure 5 shows the most contributing input values varied from −20 to +20% to assess the impacts of the varying amounts of inputs for 1 kg FPCM hemp-based milk using IMPACT 2002+. The most contributions were observed towards terrestrial ecotoxicity (66%), respiratory inorganics (11%), global warming (7.5%), non-carcinogenic (6.5%), and non-renewable energy (5%). However, with changes in the parameters, only minor variance has been observed, which indicates the reliability of the hemp-based milk production system. As the majority of the impacts derive from hemp cultivation and seed production, a 20% reduction of the processes involved in the seed production process was shown to optimize the impacts.

4.4 Assumptions and limitations in the study

This was the first LCA study on hemp-based milk; therefore, data limitations and assumptions occurred at different stages of this study. Furthermore, the hemp cultivation or yield could be affected due to a lack of knowledge or ideal equipment for hemp or due to the lack of optimum hemp cultivation methods as hemp cultivation is reintroduced in Germany after several years of ban on its cultivation. Several oversimplifications and assumptions have been made (data on tillage and sowing), which raises the probability of differences between the findings of this study and those of related experimental studies in the future. Some data inaccuracy resulted in errors and uncertainty of the results (e.g., irrigation data). For more reliable results, data is needed over several years to generate reliable figures, as seasons and weather can result in variations and affect agricultural practices. Due to the attributional method chosen, we considered only the system's sustainability and not the consequences on the market. Some information is taken from secondary sources such as ecoinvent, leading to differences in environmental impact, such as the yield of seeds or fiber. This is due to the geographic differences across countries that use different cultivation methodologies, farmers' knowledge, and

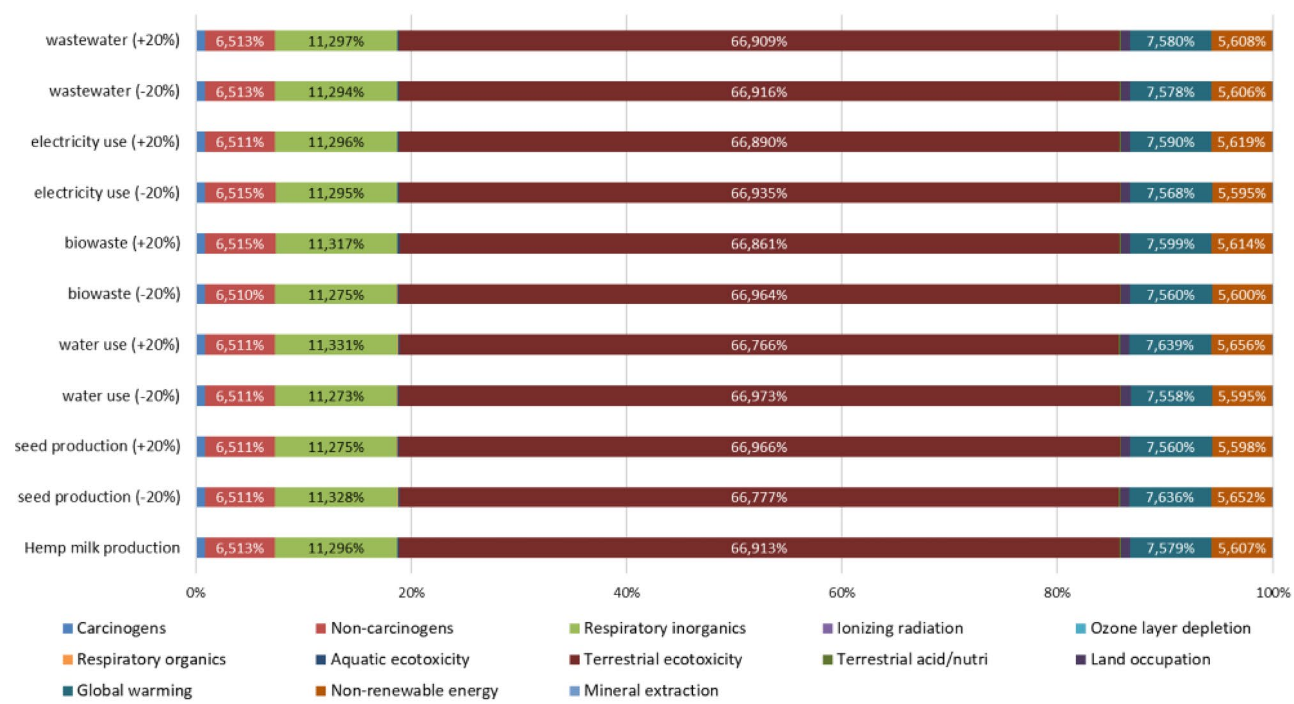

Fig. 5 Sensitivity analysis of 1 kg FPCM hemp-based milk with −20% and +20% variation

weather conditions. The underlying data were only based on literature data and database usage. Localizing the background processes was not always acceptable, and not all background processes used from the database were specific to the actual activity. Another consideration is the allocation used in this study, as the price of straw and seeds were not available to the farmers. Different prices of the product and by-products across the value chain could lead to additional uncertainty in the LCA study. The prices employed, however, are only sometimes appropriate to large-scale hemp milk production because they are frequently less expensive for large-scale production than for private usage. Additionally, prices of hemp production, hemp fiber, and hemp seeds from the factory gate could vary yearly, affecting the allocation studies. The environmental impacts may vary significantly based on local conditions (climate, energy sources, agricultural practices). However, due to the lack of recent LCA studies on hemp cultivation, this study could not be compared to other studies in the region.

5 Conclusion

For the first time, this study presented the comparative life cycle assessment of hemp-based milk and bovine milk production utilizing nutritional correction. The primary goal was to perform the LCA to examine the environmental impacts, considering milk standardization for a fair comparison with bovine milk. Therefore, the study used 1 kg FPCM as FU and relied on cradle-to-production gate system boundaries.

Life cycle assessment results showed more than two times higher environmental impacts in bovine milk production (1.204 mPt per kg FPCM) than in hemp-based milk production (0.55 mPt per kg FPCM). This was predominantly due to the lesser inputs and resource use in hemp production than in dairy milk production. Considering the midpoint impact categories, the highest environmental impacts in hemp-based milk production were pointed for terrestrial ecotoxicity (6.444E2 kg TEG soil) and aquatic ecotoxicity (2.458E2 kg TEG water) whereas, for bovine milk production, the highest impact categories were global warming (0.87 kg CO_2 eq), land occupation (11.91 m^2 org. arable), non-renewable energy (5.31 MJ primary), and ionizing radiation (3.38 Bq C-14 eq). These results demonstrate that hemp-based milk production offers the potential for being a more sustainable drink alternative than bovine milk.

The environmental impact of hemp production could additionally depend on the geographic location. Though there are other PBMPs available in the market, not all types could be made available due to a lack of resources or cost of accessibility in the region to produce or import certain kinds of PBMP. Since hemp crops can grow in most geographic locations with fewer inputs for growth (Nasrollahzadeh et al. 2022), they have more potential in terms of accessibility.

At the same time, some limitations of plant milk should be noted. Hemp or other plant-based milks are not always adequate substitutes for cow's milk in terms of nutrients. Producers often fortify the PBMP with macro and micronutrients (Aydar et al. 2020; Paul et al. 2019). Several challenges in adopting PBMP include lack of adequate knowledge, accessibility, consumer acceptance, nutritional differences, and cost. Some plant-based beverages often have a beany flavor and distinct texture, which could be less appealing to some consumers. Additionally, some consumers could be allergic or sensitive to certain products, such as nuts or soy, which is an added concern for the manufacturers of PBMP. Despite these concerns, the PBMP market is expected to grow exponentially. Meanwhile, hemp-based milk or other plant-based alternatives might be the best replacement for cow milk if a person has no other dietary deficiencies, chooses vegan products, is environmentally conscious or concerned about animal rights, has lactose intolerance or milk allergies, and wants to lose weight or control their diabetes or cholesterol.

This study follows the rising tendency to implement LCA methodology in German agricultural production systems. The results can be used locally and globally with similar climatic conditions and production techniques.

Author contribution JF: formal analysis, methodology, investigation, writing—original draft. BdS: formal analysis, methodology, writing—review and editing, supervision. SS: conceptualization, methodology, formal analysis, writing—review and editing, supervision, funding acquisition. M-CB: experimental data supply, review and editing, supervision. NT: stakeholder communication, review and editing, supervision.

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Data availability All data supporting this study are included within the article.

Declarations

Competing interests The authors declare no competing interests.

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Authors and Affiliations

Jannatul Ferdouse[1] · Beatriz Q. Silva[1,2] · Marie-Christin Baune[1] · Nino Terjung[1] · Sergiy Smetana[1,3]

✉ Sergiy Smetana
s.smetana@dil-ev.de

1 German Institute of Food Technologies (DIL e. V.), Professor-von-Klitzing-Straße 7, 49610 Quakenbrück, Germany

2 Universidade Católica Portuguesa, CBQF – Centro de Biotecnologia e Química Fina – Laboratório Associado, Escola Superior de Biotecnologia, Rua Diogo Botelho 1327, 4169-005 Porto, Portugal

3 Institute of Food Quality and Food Safety, University of Veterinary Medicine Hannover, Foundation, Bischofsholer Damm 15, D-30173 Hannover, Germany