Sustainable Food Technology

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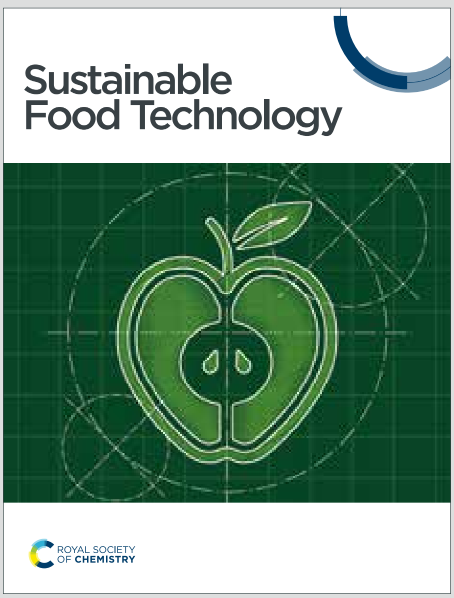

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Sustainability Spotlight Statement

Advancing sustainable nutrition necessitates food systems that minimize environmental burdens while simultaneously support economic feasibility and viability. The present work demonstrates that faba beans, due to their nitrogen-fixing capacity, low-input cultivation requirements, and high protein content, offer a promising foundation for climate-conscious beverage production. Through integrated LCA and LCC analyses, energy-intensive steps, like decantation and drying, were identified as key hotspots and highlight opportunities for improvement through alternative fractionation, energy-efficient processing, and sustainable packaging. By optimising these stages, faba-based beverages can achieve lower carbon footprints and reduced resource use while remaining cost-competitive. This research aligns strongly with the UN SDGs on responsible consumption and production (SDG 12), climate action (SDG 13), and industry, innovation, and infrastructure (SDG 9).

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ARTICLE

Sustainable and Cost-Effective: The Environmental and Economic Advantages of a Model Plant-Based Beverage

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The rising demand for healthy and sustainable food options has led to a growing interest in alternative, plant-based beverages. The present study aimed to evaluate the environmental and economic impacts of a model nutritional beverage base composed of faba bean protein and maltodextrin, using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies. The study adopted a cradle-to-gate system boundary to analyse the entire production process, taking into consideration faba bean cultivation, protein isolate production, and beverage manufacturing. Faba beans are considered a promising sustainable ingredient due to their high protein content, in-field nitrogen-fixing ability and pollinator promotion potential. Across the production process, it was demonstrated that faba beans can provide a protein platform for the sustainable production of a nutritional beverage. Additionally, this study provided a holistic evaluation to guide the development of sustainable plant-based beverages, with findings underscoring the need for innovations such as alternative fractionation methods, energy-efficient processing technologies, and sustainable packaging to further enhance the environmental and economic profile of this beverage. The LCA results highlighted the energy-intensive nature of involved processes, such as decantation and spray-drying, and the utilization of conventional packaging materials as the primary contributor to climate impact, fossil depletion, and fine particulate matter formation, with the corresponding values being 0.229 kg CO_2 eq., 0.078 kg oil eq., and 4.81×10^{-5} kg PM2.5 eq. per 330 mL of the model beverage, respectively. Owing to the crop's ability to naturally fix atmospheric nitrogen, fertiliser use during cultivation is minimal. The periodic requirement for phosphorous and possibly potassium led to the value rising up to 2.34×10^{-5} kg P eq. per 330 mL of the model beverage. Economically, protein isolate and beverage production dominated costs, mainly due to the energy and labor demands of involved processes, with cultivation contributing less. The total cost associated with producing 330 mL of the two-component beverage is approximately € 0.46. Collectively, this study provides a holistic evaluation to guide the development of sustainable plant-based beverages, highlighting the environmental and economic advantages of faba-bean for the development of functional food products.

Introduction

Beverages are an essential part of human diets, impacting both health and cultural practices. [1,2]. Specifically, beverages can be a source of nutrition for consumers, significantly contributing to hydration, and are closely connected to societal traditions worldwide [3]. However, conventional beverage production is often associated with environmental and economic issues and challenges, such as high water and energy consumption, generation of plastic wastes and price volatility of raw materials [4–6]. Therefore, environmental and economic sustainability is an important factor for food and beverage manufacturers to improve competitiveness and meet consumer demands [7]. Additionally, many beverages exhibit high sugar content, thus raising public health concerns, including obesity and metabolic disorders [8]. Global demand for sustainable and health-conscious alternatives has increased significantly over the last few years, with the plant-based food market exceeding USD 40 billion in 2022 and expected to grow at a compound annual growth rate above 10% [9], resulting in a need to balance environmental responsibility with consumer needs [10].

The utilisation of legumes as an alternative source of protein in the human diet is considered an appealing pathway towards the development of sustainable food products with high nutritional value [11,12]. Faba beans are a well-known legume species with strong nutritional and agronomic attributes, offering promising potential for developing novel plant-based food products, including beverages [13,14]. Faba beans (*Vicia faba*) can serve as a

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versatile ingredient to meet rising global nutritional demands due to their high protein content, dietary fibers, and essential micronutrients [15]. Furthermore, faba beans are nitrogen-fixing crops, enhancing soil fertility and reducing the use of synthetic fertilisers [16]. The aforementioned attributes position faba bean as an ideal candidate for sustainable food innovations, including producing plant-based beverages that can address health and environmental concerns. However, in parallel to the importance of product design and development it is equally important to evaluate the environmental sustainability and economic viability of such products to highlight their potential as novel ingredients in beverage manufacturing.

Life Cycle Assessment (LCA) is a valuable framework used for evaluating the environmental impacts of product systems by considering all relevant aspects throughout their life cycle, including inputs, outputs, and potential environmental impacts [17]. The primary goal of LCA is to pinpoint significant environmental hotspots at different stages during the production phases and provide insightful recommendations that can improve the environmental sustainability of the product system [18]. Similarly, Life Cycle Costing (LCC) is an essential framework that assesses the total economic costs attributed to a product system throughout its entire life cycle by considering all relevant cost flows, including investment, operating and end-of-life expenditures [19]. LCC analysis is vital in identifying critical cost hotspots across different stages while proposing strategies/mitigation measures to optimise overall economic performance and guide stakeholders on sustainable decision-making [20].

The primary goal of the present work was to evaluate the environmental and economic footprint of a plant-based model beverage, utilising faba bean protein isolate as a base nutritional component, through LCA and LCC analyses. An assessment of the production processes in terms of environmental and economic sustainability aims to determine the feasibility of producing the faba bean-based beverage. Generally, faba beans are not widely used for commercial beverage production; therefore, the studied beverage model can be considered an innovative alternative rather than a direct substitute for soy or other plant-based nutritional drinks. Consequently, it cannot be directly compared in terms of environmental and economic performance with other conventional products that already exist in the market. The novelty of this work lies in its holistic approach throughout the different stages of the production chain, combining environmental and economic assessments to guide the development of innovative and sustainable food solutions, and in the evaluation of a novel faba-based beverage.

Methodology

The LCA study followed the guidelines outlined in the relevant ISO 14040 series (ISO 14040:2006 and ISO 140:2006) [21,22]. An impact assessment was conducted using the ReCiPe 2016 (Hierarchist) method, which is designed to transform life cycle inventory data into a streamlined set of environmental impact scores using characterisation factors [23]. The hierarchist perspective represents a consensus-based approach aligned with commonly accepted scientific and policy assumptions, and is widely used as the default in LCA studies. The analysis was conducted using LCA for Experts software (version 10.6.2.9) developed by Sphera Solutions GmbH, located in Echterdingen, Stuttgart, Germany. The life cycle inventory is presented in the relevant section, and the Life Cycle Impact Assessemtn calculation was performed by applying ReCiPe characterization factors to convert inventory flows into midpoint and endpoint impact indicators.

LCC analysis was performed using Microsoft Excel (v15.0) and involved identifying all relevant economic flows. For the present work, only operating expenditures (OPEX) were considered, and capital expenditures (CAPEX) were excluded. CAPEX was not considered, since the production of the model faba-bean protein based beverage can be completed using equipment and process lines that are considered conventional within the food and beverage sector.

Goal & Scope

The primary objective of the current study was to assess the environmental and economic footprint of a model nutritional beverage featuring faba bean protein isolate as its primary ingredient. The beverage production flowchart (Figure 1) is comprised of three main components: faba beans cultivation, faba bean protein isolate production, and beverage production. The processes involved in the three production components were thoroughly investigated, and data were collected for each process separately. Specifically, for the part of faba bean protein isolate production, the process is a scaled-up version of to the alkaline solubilization and acidic precipitation process outlined by Kamani et. al. (2024) with the solids content of neutralized material before drying being approximately 12% [24].

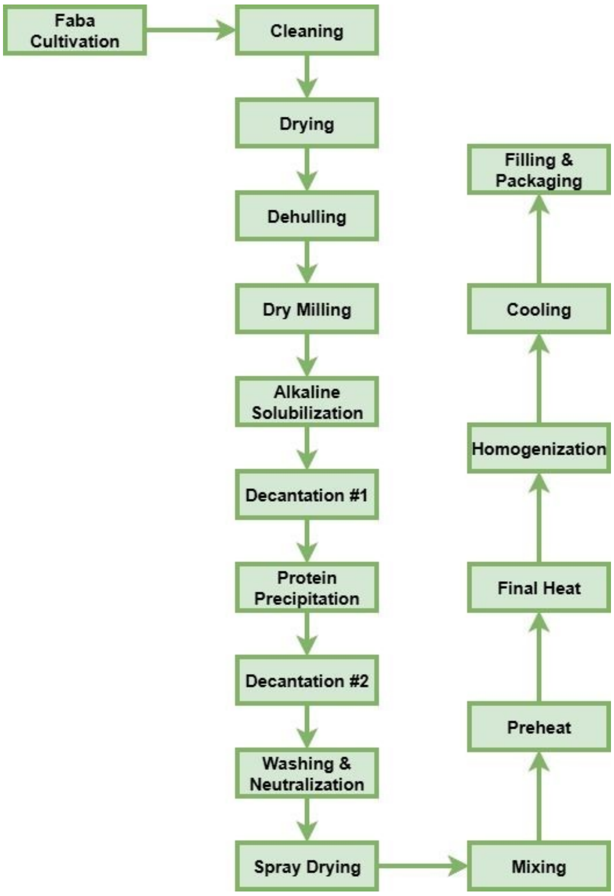

Fig. 1 Flowchart of beverage production

Functional Unit

The selected functional unit for the present work was 1 unit of packaged beverage (330 mL). The density of the model beverage is 1038 kg/m^3.

Beverage Composition

For the production of the model beverage, only three ingredients were used. Specifically, for producing 1 kg of the model beverage, 0.89, 0.06, and 0.05 kg of water, faba bean protein isolate (90.12% protein content) and maltodextrin were used, respectively. The applied recipe for the model beverage was intentionally selected to be uncomplicated; therefore, fat and micronutrients, including minerals and vitamins, were not added, as the main purpose of the present study was to evaluate the direct impact of faba bean protein isolate on model beverage production. Protein is, for the most part, considered the nutritional base of a formulation and contributes significantly to the cost of ingredients. While this cost is only part of the overall cost of goods, the processes used to extract the protein, the quantity used in a formulation, and the functionality imparted during processing are the primary focus of the project component. Maltodextrin was added as it provides the energy component of the beverage and can, by itself or through interactions with proteins, alter viscosity, thereby affecting concentration and subsequent drying efficiency. The formulation in the study is thus based on the two ingredients that can impact processing efficiency and, consequently, the cost of manufacture. It is assumed that the inclusion of additional ingredients will not significantly affect the beverage's environmental and economic performance, as their levels are low and they are more inert, i.e., they have minimal impact on process efficiency. Finally, the selected processes involved in the production of the model beverage are a replica of commercial processes used in the production of beverages already existing in the market.

System Boundaries

A cradle-to-gate approach was used to evaluate the environmental and economic footprint of the beverage production. According to the selected approach, LCA and LCC analyses encompass the extraction of raw materials up to the point at which the finished beverage is ready to exit the production facilities and be distributed to the market [21]. The current approach is particularly useful for assessing production-related impacts and highlighting areas for improvement within the boundaries of the manufacturing phase that better aligns with the main scope of the present work.

Data Requirements – Assumptions and Limitations

The present work utilised data that were collected by communication with different stakeholders located in Ireland that are involved in the three different components of the production chain. Specifically, data regarding the cultivation of faba beans were collected following communication with Irish farmers and data related to the protein isolate and beverage production were obtained from relevant industries located in Ireland. All data were collected with prior informed consent from the respective farmers and industrial partners. Furthermore, data were generated based on pilot trials, first-principle calculations and expert consultation. Additionally, reputable scientific databases, such as Ecoinvent and LCA for experts, were utilised, with data tailored to the Irish context. Finally, the values for the cost flows associated with the cultivation of faba beans were obtained from a report by Teagasc in 2024, which is the Agriculture and Food Development Authority of Ireland [25]. While these sources ensure a robust representation of the current production practices, some variability in data may arise due to differences in productivity and methods among stakeholders. Nevertheless, they are not expected to influence the results significantly. By consistently applying the same data sources and assumptions across all stages of the analysis, the potential impact of variability is minimised, ensuring the reliability of the findings.

LCA and LCC Inventory

Data utilised in the present work are presented in the following tables (Tables 1-6). To thoroughly evaluate the environmental and economic footprint and conduct a comprehensive analysis of the beverage production process, it was decided to study not only the aggregated Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) but also the footprint of individual components within the production chain. Therefore, the inventory analysis and its findings will be presented comprehensively, encompassing both the overall perspective and a detailed examination of each individual component within the production process.

Table 1. LCA inventory of faba beans cultivation

Process	Flow	In/Out	Value	Unit
Cultivation	Diesel	In	78	L
	Fungicides	In	3	L
	Herbicides	In	9	L
	Insecticides	In	0.05	L
	Potassium fertilizer	In	60	kg
	Phosphorus fertilizer	In	40	kg
	Cultivation area	In	1	ha
	Faba beans	Out	5500	kg

Table 2. LCC inventory of faba beans cultivation [25]

Flow		Unit	Value	€/unit	Cost (€)
Utilities	Diesel	L	78	1.63	127.14
Chemical agents	Fungicide	L	3	13	39
	Herbicide	L	9	15	135
	Insecticde	L	0.05	12	0.6
Fertilisers	P fertiliser	kg	40	1.4	56
	K fertilizer	kg	60	0.9	54
Labor	Working hours	Hours	21	15.86	333.06
Output	Faba beans	kg	5500	Total	741.8

Table 3. LCA inventory of faba beans protein isolate production

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Process	Flow	In/Out	Value	Unit
Cleaning [a]	Faba beans (wet/dirty)	In	1181.25	kg
	Electricity	In	3.6	MJ
	Clean faba beans	Out	1125	kg
	Foreign material	Out	56.25	kg
Drying [b]	Clean faba beans	In	1125	kg
	Electricity	In	608	MJ
	Faba beans	Out	1000	kg
	Water vapor	Out	125	kg
Dehulling [c]	Faba beans	In	1000	kg
	Electricity	In	18.45	MJ
	Dehulled faba beans	Out	800	kg
	Faba beans hulls	Out	200	kg
Dry Milling [c]	Dehulled faba beans	In	800	kg
	Electricity	In	46.7	MJ
	Faba flour	Out	800	kg
Alkaline Solubilization [c]	Faba flour	In	800	kg
	Sodium hydroxide (10%)	In	43.2	kg
	Water	In	7200	kg
	Protein solution	Out	8043.2	kg
Decantation #1 [a]	Protein solution	In	8043.2	kg
	Electricity	In	198.5	MJ
	Dried cake	Out	396.27	kg
	Protein solution	Out	7567.36	kg
Protein Precipitation [c]	Protein solution	In	7567.36	kg
	Hydrochloric acid (10%)	In	105.98	kg
	Protein solution	Out	7673.34	kg
Decantation #2 [a]	Protein solution	In	7673.34	kg
	Electricity	In	275.4	MJ
	Acidified water	Out	6759.71	kg
	Protein cake	Out	913.63	kg
Washing & Neutralization [c]	Protein cake	In	913.63	kg
	Sodium hydroxide (10%)	In	9.37	kg
	Deionised water	In	455.25	kg
	Protein solution	Out	1378.25	kg
Spray Drying [a,b]	Protein solution	In	1378.25	kg
	Electricity	In	167.2	MJ
	Thermal energy from natural gas	In	4820.57	MJ
	Faba protein isolate	Out	173.11	kg
	Water vapor	Out	1205.14	kg

[a] Data from industry expert consultation

[b] Derived from fundamental theoretical calculation

[c] Data from pilot scale operation

Table 4. LCC inventory of faba beans protein isolate production

Flow		Unit	Value	€/unit	Cost (€)
Utilities	Electricity	MJ	1317.85	0.1121	147.73
	Natural gas	MJ	4820.57	0.04	192.82
Water	Process water	kg	7200	0.00185	13.32
	Deionised water	kg	455.25	1	455.25
Auxiliary Materials	Sodium Hydroxide	kg	52.57	0.4	21.03
	Hydrochloric acid	kg	105.98	2.5	264.95
Labor	Working hours	Hours	16	16.46	263.36
Wastewater	Acidified water	kg	6759.71	0.00182	12.3
Solid Wastes	Hulls	kg	200	0.105	21
	Foreign material	kg	56.25	0.105	5.91
	Dried cake	kg	396.27	0.105	41.61
Output	Faba beans protein isolate	kg	173.11	Total	1439.28

Table 5. LCA inventory of beverage production

Process	Flow	In/Out	Value	Unit
Mixing [a]	Faba protein isolate	In	60	kg
	Maltodextrin	In	50	kg
	Water	In	890	kg
	Electricity	In	9.5	MJ
	Beverage	Out	1000	kg
Preheat [b]	Beverage	In	1000	kg
	Natural gas	In	6	Nm3
	Steam	In	311.35	kg
	Beverage	Out	1000	kg
Final Heat [b]	Beverage	In	1000	kg
	Natural gas	In	10.1	Nm3
	Steam	In	134.56	kg
	Beverage	Out	1000	kg
Homogenisation [b]	Beverage	In	1000	kg
	Electricity	In	43.2	MJ
	Beverage	Out	1000	kg
Cooling [b]	Beverage	In	1000	kg
	Electricity	In	116	MJ
	Beverage	Out	1000	kg
Filling & Packaging [c]	Beverage	In	1000	kg
	Electricity	In	19	MJ
	PET bottles	In	46.97	kg
	Beverage	Out	1000	kg

[a] Data from pilot scale operations

[b] Derived from fundamental theoretical calculation

[c] Data from industrial scale operations

Table 6. LCC inventory of beverage production

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Flow		Unit	Value	€/unit	Cost (€)
Utilities	Electricity	MJ	187.7	0.1121	21.04
	Natural gas	Nm^3	16.1	1.725	27.77
	Steam	kg	445.91	0.42	187.28
Water	Process water	kg	890	0.00185	1.65
Auxiliary Materials	Maltodextrin	kg	50	4.25	212.5
	PET bottle	kg	46.97	1.19	55.89
Labor	Working hours	Hours	16	16.46	263.36
Output	Beverage	kg	1000	**Total**	769.49

Results and Discussion

LCA Results

The total environmental impact of the model beverage production, including all relevant processes, across the studied midpoint categories is presented in Figure 2.

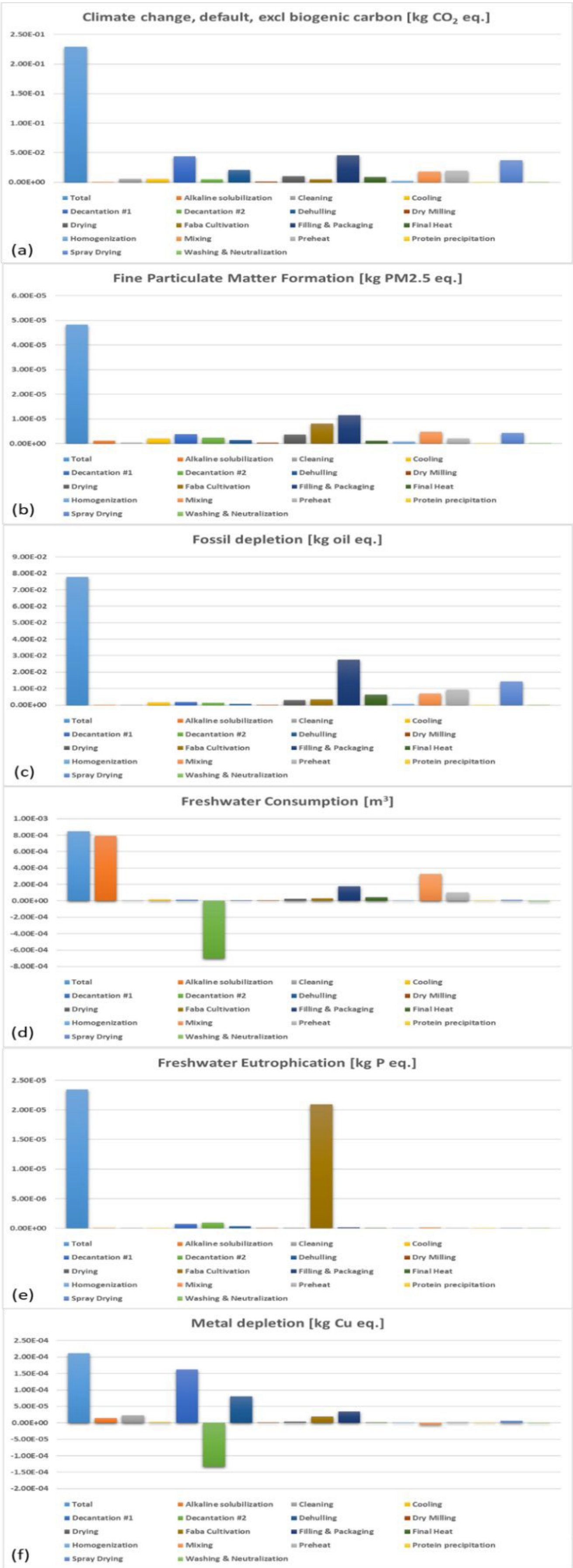

Fig. 2 Environmental impact of the beverage production on (a) climate change (kg CO_2 eq.), (b) fine particulate matter formation (kg PM2.5 eq.), (c) fossil depletion (kg oil eq.), (d) freshwater consumption (m³), (e) freshwater eutrophication (kg P eq.) and (f) metal depletion (kg Cu eq.)

According to the LCA results, the use of energy-intensive processes during faba bean protein isolate manufacture and beverage production is the primary contributor to environmental impact. Among the production stages, the filling and packaging, decantation and spray-drying processes are identified as the most impactful, contributing to climate change, fossil depletion, and fine particulate matter formation (0.229 kg CO_2 eq., 0.077 kg oil eq., and 4.81×10^{-5} kg PM2.5 eq. per 330 mL of beverage, respectively). This is attributed to the energy use and packaging materials of the filling and packaging, along with the energy use of spray-drying and decantation processes and the use of sodium hydroxide during alkaline solubilization [26–28]. On the other hand, freshwater consumption (8.45×10^{-4} m³ per 330 mL of beverage) is relatively unaffected by cultivation since faba beans are not irrigated. However, the use of fertilisers during cultivation has the potential to contribute to eutrophication risk (2.34×10^{-5} kg P eq. per 330 mL of beverage), in circumstances where crop management does not mitigate nutrient runoff potential [29]. Finally, dehulling and the first decantation process contribute to metal depletion (2.12×10^{-4} kg oil eq. per 330 mL of beverage) due to the electricity consumption and the generation of solid wastes, respectively [26,30]. The difference in the performance of the two decantation processes in some environmental metrics, such as freshwater consumption and climate change, is attributed to the different output stream subsequently processed in the process line. Specifically, during the first decantation the dried cake is considered as a side-stream that is disposed, while the protein solution is undergoing further treatment. On the other hand, on the second decantation process the acidified water is treated in a municipal wastewater treatment plant, thus it is treated and can return to the aquatic environment [31], while the protein cake is further treated to obtain the protein isolate.

Faba bean-based beverages are not well-established in the marketplace, so the results of the present work cannot be directly compared with other studies. However, it is insightful to compare them with other plant-based drinks. According to published articles, the carbon footprint of almond, soy and oat beverages is 0.154, 0.175, and 0.099 kg CO_2 eq. per 330 mL of product, respectively [32–34]., compared to the faba bean result of 0.229 kg CO_2 eq. However, it is worth noting that in the aforementioned studies, the drink was produced using slightly processed crops (i.e. dehulled or washed crops), and not a protein isolate, therefore, the environmental footprint is lower compared to the present study. On the other hand, the utilisation of protein isolate can increase protein concentration, improve solubility, reduce off-flavors, and minimise anti-nutritional factors, providing a smoother and more appealing final product [35,36].

A detailed breakdown of each beverage production component contribution in the studied midpoints is depicted in Figure 3.

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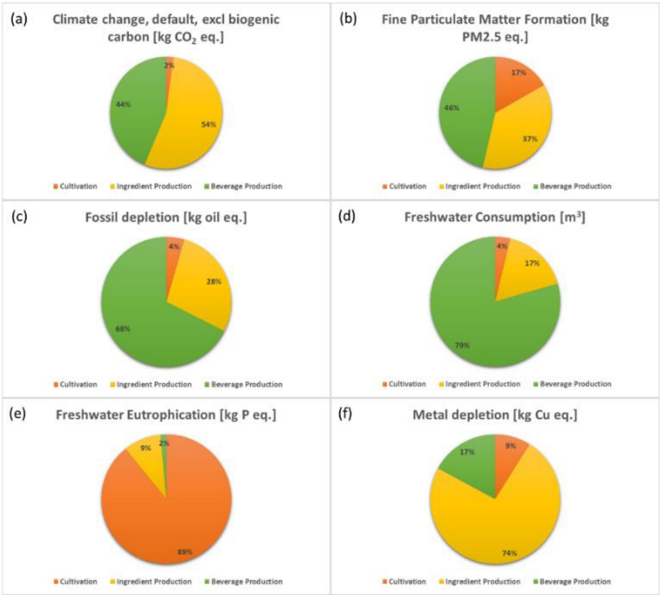

Fig. 3 Contribution of each beverage production component in (a) climate change (kg CO_2 eq.), (b) fine particulate matter formation (kg PM2.5 eq.), (c) fossil depletion (kg oil eq.), (d) freshwater consumption (m^3), (e) freshwater eutrophication (kg P eq.) and (f) metal depletion (kg Cu eq.)

The LCA results highlight the distinct contributions of cultivation, ingredient production, and beverage production across the various environmental categories studied. The third component of the production chain, namely the beverage production emerges as the dominant contributor to most impact categories, including fine particulate matter formation (46%), fossil depletion (68%), and freshwater consumption (79%) due to the energy consumption of heating and filling & packaging processes, along with the inclusion of packaging materials and the use of water as the basis for the beverage production. In contrast, cultivation as with standard cropping systems presents a risk of freshwater eutrophication in the absence of crop mitigation measures due to fertiliser use but has minimal influence on freshwater consumption (4%), as faba beans in the studied product system are not irrigated. However, in other pedoclimatic regions with limited rainfall, faba beans may need irrigation, and thus, freshwater consumption will differ. On the other hand, ingredient production is the primary contributor to climate change (54%) and metal depletion (74%) due to the inclusion of energy-intensive processes such as decantation and spray-drying. Particularly, for the fine particulate matter formation, faba cultivation exhibits a significant role, which is attributed to the utilization of diesel in agricultural machinery, required for cultivation practices [37]. It is worth noting that regarding freshwater consumption in which beverage production predominantly contributes, it is attributed to the use of water that is necessary for the production of beverage, while the vast majority of water utilized during the ingredient production is treated in wastewater plants and returned to the aquatic environment. This breakdown highlights the importance of targeted improvements in energy efficiency during protein isolate and beverage production, as well as the utilisation of soils with high P and K indices, resulting from optimal pH and effective system management.

The endpoint analysis of the LCA offers a comprehensive perspective on the environmental impacts of beverage production, focusing on three key areas: human health, ecosystems, and resource availability [38]. Figure 4 illustrates the aggregated effects of the different production components across these categories, highlighting their broader environmental implications.

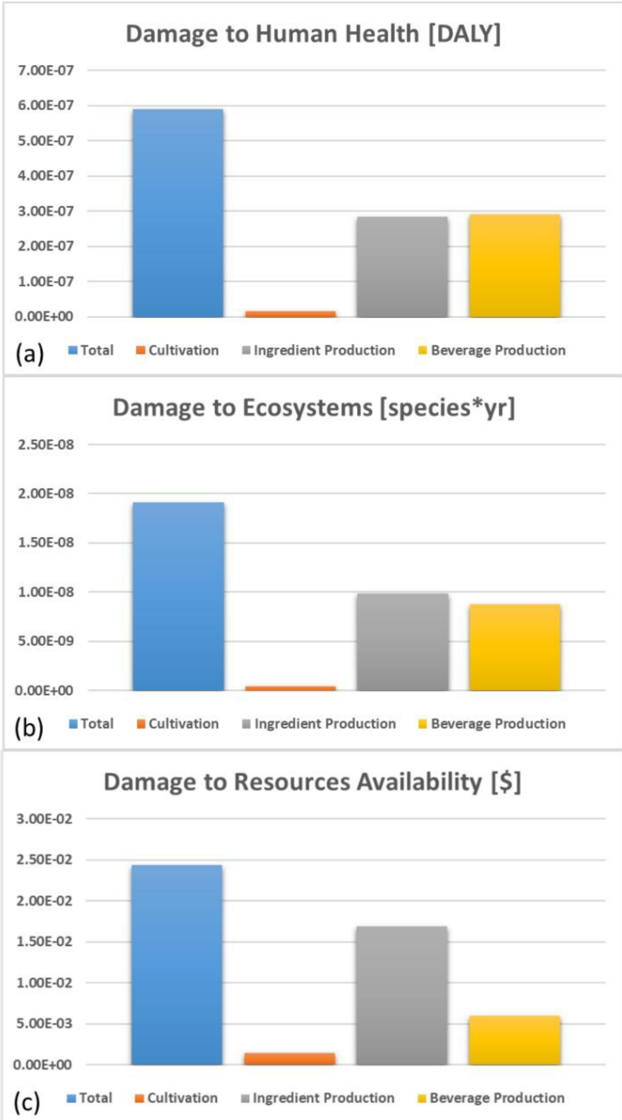

Fig. 4 ReCiPe endpoints of the beverage production

The results of the ReCiPe endpoints indicate that the ingredient production exhibits the highest contribution regarding impact on ecosystems, and resources availability, while beverage production is the highest contributor in impact on human health. Specifically, beverage production accounts for the largest share in impact on human health (5.91×10^{-7} DALY), while ingredient production plays a secondary role. On the contrary, faba protein isolate production exhibits the highest impact on ecosystems, compared to the cultivation and beverage

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production phases, with the total value rising up to 1.91×10^{-8} species*year. This can be attributed to the substantial quantities of resources used to produce the protein isolate. Finally, regarding resource availability, ingredient production is led by its reliance on energy-intensive inputs, with a total value of 2.433×10^{-2} \$. Cultivation has a minimal impact in all categories, reflecting its comparatively low resource demands.

LCC Results

The results regarding the economic footprint of the novel faba bean-based beverage are expressed per 330 mL of the final product. Figure 5 illustrates the total cost associated with the production processes, similar to the LCA results. Moreover, two additional cost flows are considered, namely maintenance and other costs. Each of the aforementioned costs equals 5% of the total production costs, with maintenance costs attributed to expenses associated with maintaining all necessary equipment and machinery, as well as other costs related to taxation and similar cost flows.

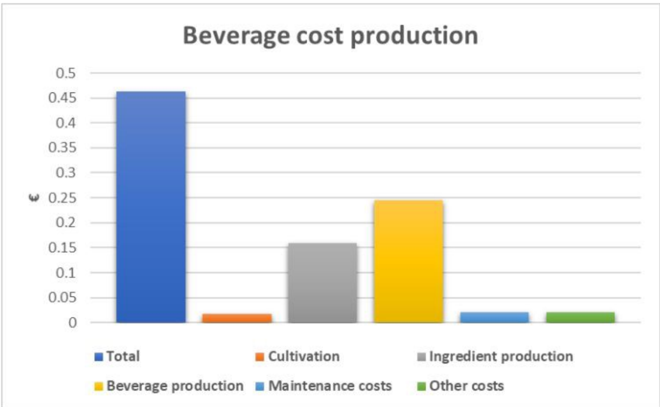

Fig. 5 Total cost and cost per production component for producing 330 mL of beverage

The beverage cost analysis provides a comprehensive breakdown of the financial contributions from various production stages, offering valuable insight into where resources are allocated. According to the obtained results, 0.46 € are required to produce 330 mL of the beverage, considering all operating expenditures across the three different compounds of the production chain. Beverage production is the dominant contributor to the total production cost, with 0.24 €. This is largely due to the energy demands associated with heating and the utilization of conventional packaging materials in the packaging & filling of the final product, and constitute a key factor especially as consumer demand for premium packaging and efficient delivery systems increases. Protein isolate production ranks as the second largest contributor, a production component that encompasses various activities requiring significant quantities of energy, labour, and materials. While less costly than beverage production, ingredient production (0.16 €) remains a key factor. Maintenance and other costs represent the third largest contributor to the overall production cost (0.021 € each). These include expenses associated with equipment upkeep, repairs, operational overheads and any other relevant cost flow. Finally, cultivation contributes the least to the total cost with the total costs for producing the necessary quantities of faba bean for 1 beverage rising to 0.018 €. This indicates efficient agricultural practices or the use of low-cost, non-irrigated crops that require minimal input, such as fertilisers or water. While cultivation costs are minimal, they remain an important foundation for the supply chain, as the quality of raw ingredients directly affects the attributes of the final product. A detailed breakdown of the ingredient and beverage components cost flows is depicted in Figure 6. The corresponding results for the cultivation component are not presented, since the costs associated with this phase are lower compared to the other components and do not influence the economic footprint of the final product.

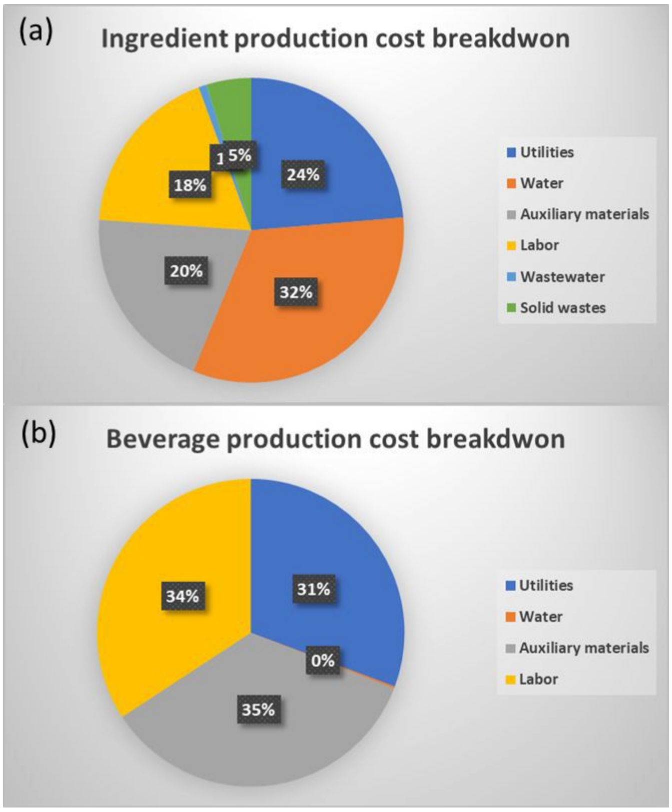

Fig. 6 Cost flows breakdown on (a) faba beans protein isolate production, and (b) beverage production

The cost breakdown analysis highlights the varying contributions of ingredient production, and beverage production to the overall cost structure. Ingredient production shows a predominance of water associated costs, representing 32% of the total cost, with deionizing water playing a major role. Utilities costs accounts for 24%, while auxiliary materials and labor contribute 20% and 18%, respectively, with minimal costs being allocated to wastewater and solid wastes. Finally, regarding beverage production cost breakdown, auxiliary materials, labor and utilities contribute significantly to the cost structure, with 35%, 34%, and 31% contributions, respectively. On the contrary, costs associated with water can be characterized as negligible.

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Challenges and Future Perspectives

According to the LCA and LCC results, several hotspots have been identified during the production of the faba beans-based beverage. Among them, the most significant include energy intensive processes, like drying, used in the manufacture of faba bean protein isolate powder and thermal treatment of the beverage, along with the filling and packaging of the final product.

One of the main challenges in producing protein isolates utilising the conventional wet fractionation process is the environmental and economic footprint associated with consecutive decantation steps and spray drying. Decantation is widely used to separate solid and liquid phases following extraction or solubilization, but the process often requires continuous rotational forces and high shear operation to achieve sufficient clarity and yield. These demands result in elevated energy consumption, increased equipment wear, and greater operational costs, particularly when large volumes of dilute suspensions must be processed.[39]. Meanwhile, spray drying is an energy-intensive process contributing significantly to production costs and environmental impact [34]. Evaporation is widely used for many feedstocks prior to spray drying to reduce the volume of material subjected to subsequent drying, thereby saving energy [40,41] . The viscosity of the feed material determines the extent to which a liquid feed can be concentrated. Therefore, the type, quantity, and functionality of protein directly affect process efficiency by determining how much water can be removed before spray drying. Additionally, dry fractionation methods could replace, in the case of protein concentrates, wet processes entirely, eliminating the need for consecutive decantation steps and spray drying; however, it must be noted that these methods cannot be used to obtain protein isolates [42,43]. This approach can potentially reduce energy consumption and align with sustainability goals by lowering greenhouse gas emissions and the overall environmental footprint [44].

Optimising energy use during thermal treatment presents an important opportunity in beverage production. Innovations such as microwave or ohmic heating offer potential for more energy-efficient processing at small scales. However, their use in large-scale production can be constrained by low throughput. Packaging also presents a significant opportunity for improvement. The transition from conventional polymer-based packaging materials to biodegradable or lightweight materials could reduce environmental impact and lower costs, ensuring both sustainability and economic viability [45].

Additionally, excluding labor-associated costs, utilities, particularly energy, remain a significant cost contributor throughout the beverage production chain. Reducing energy consumption would therefore directly reduce production costs. This can be achieved through energy recovery systems and improved process efficiencies. Furthermore, investing in renewable energy infrastructure, such as solar panels or biomass energy systems, could offset reliance on conventional electricity sources. Although such investments involve high capital expenditures (CAPEX), they promise long-term economic and environmental benefits [46,47].

Generally, adopting novel technologies is vital to reduce the overall environmental footprint. However, these technologies must be carefully evaluated through a life-cycle cost (LCC) analysis to account for initial CAPEX alongside potential operational savings and sustainability benefits. For instance, advanced filtration systems or renewable energy equipment may initially require substantial investment but could significantly reduce utilities costs and greenhouse gas emissions in the long term. By balancing economic considerations with environmental priorities, the production process can be optimised to meet market and sustainability demands.

Conclusions

The primary objective of this study was to evaluate the environmental and economic impact of a model faba bean protein-based beverage. The findings identify environmental and economic hotspots throughout the production chain. LCA confirmed that energy-intensive operations, such as filling and packaging, decantation, and spray drying, are the dominant contributors to climate change, fossil resource depletion, and fine particulate matter formation. Thus, ingredient and beverage production impact the environmental performance of the model beverage, highlighting the need for energy optimisation across the production chain. Cultivation, in the majority of the studied categories, was the most environmentally friendly component of the production chain. However, it has the potential to contribute to freshwater eutrophication due to the usage of fertilisers in certain circumstances.

Life cycle costing revealed that beverage production constitutes the highest cost component, driven primarily by labour and utilities associated with heating and packaging. Protein isolate production is the second most costly stage, reflecting the resource-intensive nature of wet fractionation, multiple decantation steps, and spray drying. Although cultivation costs are comparatively low, they remain essential to overall supply-chain performance. The cost structure indicates that reducing energy use and enhancing process efficiencies could significantly improve economic feasibility.

Based on the LCA and LCC results, faba beans can be characterised as a sustainable ingredient that can be used for producing novel plant-based beverages; however, the environmental and economic performance of these products can be significantly improved. Future innovations and process optimisation present promising pathways for enhancing sustainability and reducing costs. Transitioning to renewable energy sources, adopting energy-efficient technologies, and exploring alternatives to spray drying, such as substituting wet with dry fractionation, could address the current challenges. Moreover, integrating biodegradable or lightweight packaging options can reduce environmental impacts further. While these changes require initial capital investment, which can rise to significant monetary values in some circumstances, the long-term benefits align with sustainability goals and market demands for eco-friendly, health-conscious products. Overall, this comprehensive approach positions faba bean-based beverages as a viable solution for a sustainable food system.

Author contributions

Conceptualization, F.D., T.K. and M.F.; methodology, F.D., T.K., R.A, E.M. and M.F.; software, F.D. and T.K.; validation, R.A., E.M., M.F. and R.L.; formal analysis, F.D., T.K. and M.F.; investigation, F.D. and T.K.; resources, M.F., R.L. and M.K.; data curation, F.D. and T.K.; writing—original draft preparation, F.D. and T.K.; writing—review and editing, R.A., E.M., M.F. and R.L.; visualization, F.D. and T.K.; supervision, M.F. and M.K.; project administration, R.L. and M.K.; funding acquisition, M.F. and M.K. .

Conflicts of interest

There are no conflicts to declare.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article.