Environment Systems and Decisions
https://doi.org/10.1007/s10669-022-09874-y

LCA as decision support tool in the food and feed sector: evidence from R&D case studies

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Accepted: 27 July 2022

Abstract
Biomass waste and waste-derived feedstocks are important resources for the development of sustainable value-added products. However, the provision and preparation of biomass as well as all possible downstream processing steps need to be thoroughly analyzed to gain environmentally sound and economically viable products. Additionally, its impacts are substantially determined by decisions made at early development stages. Therefore, sustainability assessment methods can support to improve the production process, reduce waste, and costs and help decision-making, at the industrial as well as policy levels. Life Cycle Assessment (LCA) is an analysis technique to assess environmental impacts associated with all product's life cycle stages. It is a well-established tool to drive development towards a sustainable direction, however, its application in the earlier research phase is surrounded by practical challenges. The overall objective of this paper is to provide an understanding of the environmental issues involved in the early stages of product and process development and the opportunities for life cycle assessment techniques to address these issues. Thus, herein two LCA case studies are presented, dealing with novel approaches for food and feed supply through implementing the valorization and upcycling of waste and side-streams, respectively. In both case studies, LCA is used as a decision support tool for R&D activities to launch environmentally sound products to market, as well as to highlight the usefulness of LCA for identifying environmental issues at an earlier stage of development, regardless of product, process, or service.

Keywords Sustainability · Food · Feed production · Circular economy · Life cycle assessment · R&D · Challenges · Ex-ante LCA · Simplified LCA

1 Introduction

Global food production is the largest human-caused pressure on earth, threatening local ecosystems and the stability of the overall system (Willett et al. 2019). This is demonstrated impressively in the planetary boundaries model (Rockström et al. 2009). Planetary boundaries were defined as the boundaries within which it was expected that humanity can operate safely avoiding human-induced environmental change on a global level. Agricultural and food sectors are globally responsible for the exceedance of approx. 50% of all boundary categories considered. Agricultural activities, as well as food production, lead to excessive nutrient inputs to terrestrial and aquatic ecosystems implying that the nitrogen and phosphorus cycles are of the greatest importance, followed by excessive land use change and biodiversity loss (Meier 2017). Therefore, providing a growing global population with healthy diets from sustainable

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Published online: 10 August 2022

food systems is an immediate challenge. Alternative protein sources and more resource-efficient production are urgently needed to respond to the increasing protein demand for the growing world`s population. This requires innovative, holistic approaches along the entire value chain as well as tools to evaluate and support progress within research, development, and production. Environmental sustainability of products/services is typically examined by using a Life Cycle Assessment (LCA). For conducting an LCA, the principles and framework are given in ISO 14040:2006, which had an amendment in 2020 as ISO 14040:2006/AMD 1:2020, and requirements and guidelines are given in ISO 14044:2006 (ISO 14044 2006; ISO 14040 2006).

According to the DIN standards, the procedure of a life cycle assessment comprises four phases. At the beginning, the objective and scope are defined. The scope of the study, including the system boundary and the level of detail, depends on the subject of the study and the intended application of the study. The functional unit and the spatial and temporal limits of the system are therefore determined. According to DIN EN ISO 14040, the functional unit is defined as the quantified benefit of a product system which is used as a comparison unit/reference basis. The second step is the preparation of a Life Cycle Inventory (LCI) quantifying the input and output flows (energy and mass flows) over the entire life cycle, followed by an impact assessment (Life Cycle Impact Assessment, LCIA) quantifying the potential effects of these material and energy flows on the environment in the impact categories defined at the beginning. A selection of impact categories, impact indicators and characterization models as well as the allocation of the LCI results to the selected impact categories (classification) and calculation of the impact indicator values has to be performed. Finally, the evaluation stage takes place, in which the results obtained are interpreted, conclusions and decisions are made or recommendations for further action are derived. The conduct of an LCA usually is an iterative process. While working on one of the stages, it is often useful and desirable to go back to earlier parts and change the settings. It is possible, for example, that the impact assessment may reveal a need for refining or changing of LCI data in order to gradually increase the degree of detail and accuracy. The iterative approach within and between phases contributes to the holistic and consistent nature of the study and the results presented in the report.

The methodology of LCA offers a well-established and standardized approach to dealing with the quantification of impacts through the entire life cycle of a product/service in various industrial domains, not just in the food and feed sector. For instance, Smetana et al. 2019, de Boer et al. 2014, and Goyal et al. 2021 focused on the implementation of LCA for quantifying the ecological impacts of food and feed products, Ott et al. 2014 used LCA methodology to evaluate the environmental performance of pharmaceutical production process. Other examples when researchers highlighted the use of LCA for designing a sustainable product and process are Kralisch et al. 2018, Nielsen and Wenzel 2002 (used washing machine as a case study), Kralisch and Ott 2017 (for the chemical process). Therefore, the use of LCA is not only supported through various policies and legislation, such as the Waste Electrical and Electronic Equipment (WEEE) Directive (EC 2006), End of Life Vehicle Directive (EC 2003), and the Renewable Energy Directive (EC 2009) but also, has nowadays become a prerequisite for the implementation of research projects on European and international level. The European Commission proposed Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) to quantify the environmental performance of a product or organisation. The European Commission proposed this under Single Market for Green Products Initiative. Such proposals or methods (PEF or OEF) are also based on the standardized LCA methodology.

(Tischner et al. 2000; Jeswiet and Hauschild 2005)Fortunately,, including LCA in the early design phases of product/process development has been on the research agenda for several years now. Accompanying R&D projects from the very beginning by means of sustainability assessment is because an incredible potential for environmental improvement exists, especially within the configuration phase of any process or product where it is assessed that about 70–80% of its final costs and environmental impacts are incurred at the initial phase of development (Tischner et al. 2000; Jeswiet and Hauschild 2005).

While various methodological and practical challenges are emerging from using LCA at the early stage of development, and are extensively discussed among the LCA community, there is an overall consensus on its suitability as a successful tool for evaluating ecological performance, resulting in a broad utilization of LCA as a decision-making tool in selecting processes, designing, and development. While van der Giesen et al. 2020, Arvidsson et al. 2018, Hetherington et al. 2013, and Kunnari et al. 2009 discussed the challenges of implementing LCA in an early phase of development, Cucurachi et al. 2018 highlighted the benefits of it. Nielsen and Wenzel 2002 and van der Giesen et al. 2020 also gave recommendations on how to overcome different challenges of using LCA during the initial stages of product development. Koller et al. 2000 presented a new method to identify, analyze, and manage potential safety, health and environmental (SHE) hazards in the development of chemical processes where the availability of data is a considerable challenge. (van der Giesen et al. 2020; Cucurachi et al. 2018; Arvidsson et al. 2018; Hetherington et al. 2013; Finnveden et al. 2009; Binaghi et al. 2005; Roy et al. 2009; Ekvall and Weidema 2004; Kunnari et al. 2009; Nielsen and Wenzel 2002; Tufvesson et al. 2012; Koller et al. 2000).

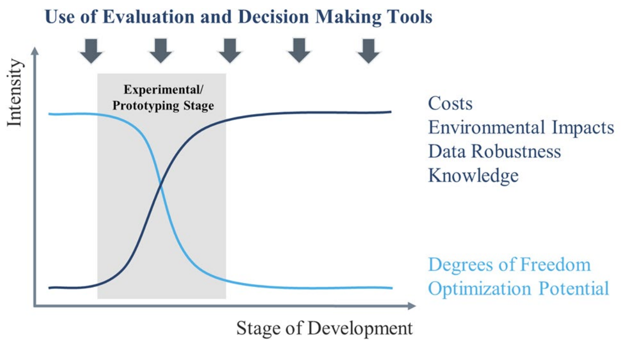

Fig. 1 Interaction of Degrees of Freedom, Optimization Potential, Costs, and Environmental Impacts, Data Robustness and Knowledge during Product and Process Development, in analogy to (Heinzle and Biwer 2001)

Figure 1 demonstrates the interactions between freedom of development, knowledge, environmental impacts, and economic costs within a development process also referred to as the Collingridge dilemma (Collingridge 1982) or dilemma of opportunity. Given the major impact early stages have on outcomes, sustainability impacts must be considered and assessed as early as possible in the technology development process, using flexible, meaningful, and reliable evaluation and decision-making tools, to avoid environmental and economic harmful end-of-pipe technologies, as the possibility to alter the technology is reduced or even locked at later stages. Despite its potential, the use of holistic life cycle assessment approaches is often not feasible at the early stages due to the limited availability of data, the uncertainty of process information and a high degree of freedom, as well as challenges related to the demand for completeness and complexity according to the ISO standards.

Therefore, simplified evaluation approaches are needed. With the help of existing data, e.g., key performance indicators and simple metrics can be determined to identify development opportunities and risks or to evaluate processes and compare alternatives (hot-spot-screening). In doing so, the orientation towards a holistic assessment is required, because solutions to problems that are optimized by considering upstream and downstream processes are more sustainable due to avoidance of problem shifting to other life cycle stages. In this context, LCA can serve as a screening method, as illustrated in the concepts of simplified/streamlined LCA (Beaufort-Langeveld and Christiansen 1997; Todd et al. 1999) as well as ex-ante LCA (Christiansen 1997; Fleischer and Schmidt 1997; Kralisch et al. 2013a, b; Kralisch et al. 2015; Cucurachi et al. 2018; Buyle et al. 2019).

As described in Klöpffer 2014, simplified LCA is an application of the LCA methodology for a comprehensive screening, reducing the complexity of an LCA by exclusion of certain life cycle stages, system inputs or outputs or impact categories, or use of generic data modules for the system under study, by simultaneously assessing reliability of the overall result. Streamlined LCA approaches works similar, however their focus is to make a full LCA more manageable by e.g., omitting elements or limiting the scope without significantly affecting the accuracy of the results. Ex-ante LCA is defined as the environmental assessment of a new technology before its commercial application, dealing with several uncertainties, e.g., concerning applications and data (Tsoy et al. 2020). (Kralisch et al. 2013a, b; Kralisch et al. 2012; 2018)In accordance with the iterative nature of LCA itself, see Fig. 2, screening, ex-ante or simplified LCA can be seen as an important starting step on the way to a holistic LCA based on accurate, precise and compete data. Applying such approaches, evaluation and decision-making progress concerning environmental impacts could be supported, allowing also coupling with further assessment methods to realize successful multi-criteria decision making (Kralisch et al. 2013a, b; Kralisch et al. 2012; 2018).

2 Challenges during the application of LCA Approaches in early R&D stages

Although different, the experience acquired through implementing LCA to analyze ecological impacts as a part of research and development show that challenges and hurdles are not dependent on technology but are common to the early phase LCA studies, though varying according to the targeted domain. Comparable challenges were reported by many researchers within their research domains (Tufvesson et al. 2012; Kunnari et al. 2009).

For LCAs on emerging innovations, industrial-scale data is unavailable, while an abundance of data is required, which may be difficult to collect at the beginning phase of process design. The assignment of data inventory is intensive for lab-scale processes, with issues, for example, for the use of new and novel raw materials, and significant differences are

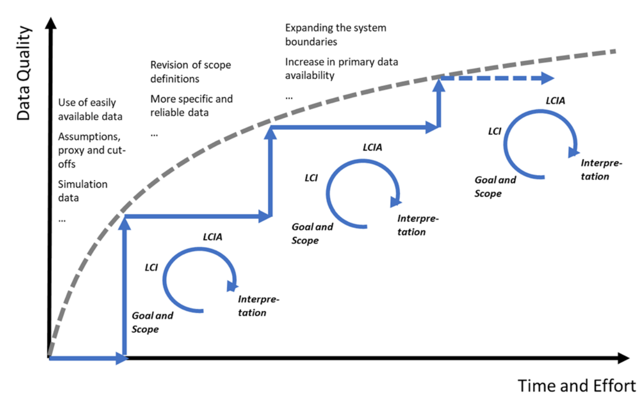

Fig. 2 Illustration of the iterative LCA workflow, in accordance with the ILCD handbook

there between lab-scale and industrial-scale processes. Such differences are well reflected in the environmental performance of the lab- and an industrial-scale process (Walser et al. 2011; Villares et al. 2016).

Different topics that can be examined within the "beginning phase" LCA are the investigation of alternative pathways for the future, with a focus on diverse feedstocks, fuel composition, and co-products. Although a lot of secondary information from many publicly available databases exists, e.g., the ELCD database (European Commission 2018), the use of less prevalent raw materials increased with the emerging technologies, creating a gap in available databases (Jiménez-González, Kim, and Overcash 2000). This forces the LCA practitioners to use proxy data of the similar process available in the database or invest a lot of time in modeling the raw materials. Additionally, lab- or even pilot-scale production processes are commonly more energy and resource-intensive, so the projected LCA impacts could be over-estimated when yield and efficiency are increased at the industrial scale of production (Villares et al. 2017; Gutowski, Liow, and Sekulic 2010; Khanna and Bakshi 2009). In general, uncertainty is associated with all such studies as also stated by Heinzle et al. (Heinzle et al. 1998): "in the design process we can never be sure whether we know all important data and interactions". If the level of uncertainty is high during an LCA, the robustness of the results will be weak, and no sound conclusion could be derived based on the findings.

While data collection is a crucial step in conducting LCA, the quality of data has its own importance. However, creating a data inventory for the modelling is one of the challenges addressed by many researchers. In the early phases of product development, data unavailability is often experienced. Amicarelli et al. 2021a, b and García-Guaita et al. 2018 emphasized on the challenge of data availability while integrating Material Flow Analysis (MFA) and LCA in the context of quantifying food waste (in Italian beef supply chain) and environmental profile of a city (in Spain), respectively. Jeswani et al. 2010 suggested that challenges like system boundary and allocation rules needs to be addressed while integrating MFA and LCA. It is the responsibility of the LCA analyst to ensure that the data collected from different stakeholders is reliable. Thus, the early-stage LCA performers must be very sensitive to the uncertainty which comes with the limited amount of data availability and ensure that the results are aligned with the LCA goal and scope of the study. All data conveyed should comply with the requirements of every partner, while sensitivities of the study should be disclosed to the beneficiaries to understand the nature of the results. Most of agri-food production systems include multifunctional processes and multiple outputs, e.g., (side) products or waste streams which can be valorised into value-added products, requiring allocation approaches, which is known as a common challenge and problem, see also Ijassi et al. 2021, especially in early-stage assessments. If allocation can`t be avoided, one of the most used allocation methods in the agri-food literature is the economic allocation, followed by physical allocation (mass or energy). Sensitivity analyses could be performed to analyse the impact of the chosen allocation method and thus robustness of results, depending on the scope and framework of the study considering a multi-stakeholder perspective.

To ensure comparability with other studies, the information provided to the different stakeholders must be very precise with detailed information on the complexities of the undertaken modeling. A clear goal and scope of the study must be defined, with care taken to ensure a consistent system boundary and functional unit of other studies used for comparison. When needed, assumptions should be acknowledged and the use of multiple functional units to enhance the comparability of the results could be considered. Amicarelli et al. 2021a, b also discussed such opportunities to enhance the replicability and comparability of LCA results in the context of food waste research.

3 From theory to practice: case studies

To highlight the importance of integrating LCA in the early phases of research and development of a product or process, first-hand experiences from two different case studies in the food and feed sector will be described. Each of the case studies discussed in this paper is at the pilot scale, or beginning phases of industrial pilot plans, by which LCA is key to ensuring reduced ecological effects. The case studies are (a) life cycle assessment of fish feed derived from plants and insects and (b) life cycle assessment of plant -based protein products for the food value chain. An introduction from LCA perspective is given in Table 1. More information, especially related to the LCA stage "Interpretation", can be found in the sections below.

Data were mainly gathered from primary sources, i.e., farmers, research institutes, food/feed processors and food/feed factories, acting as project partners in both R&D case studies. Where primary data were absent, these were substituted by secondary data, i.e., Ecoinvent or literature (scientific paper, patents, industry data). Other types of data substitutes could be simulation/ thermodynamic modelling or stoichiometric calculations, see also Beemsterboer et al. (2020). The data sources were documented accordingly in each case to ensure transparency and comparability, but some of them are not yet publicly accessible due to IPR.

Both case studies consider the use of waste streams, which are produced as well as partially consumed within the system boundary. Allocating the environmental impacts were avoided at this stage. This is due to the fact, that most

Table 1 Brief introduction of both case studies from an LCA perspective

Phases of an LCA	Case study 1	Case study 2
Goal and Scope	Cradle-to-gate assessment of the ecological profile of insect and duckweed meal production and upscaling, incl. transports No allocation, no cut-offs Functional unit: 1 kg of dry raw meal ready for pellet processing	Comparative hot-spot screening of lentil, soy, and dairy protein isolates to identify the ecological (and economic) potential and challenges prior to product development Functional unit: 1 kg of protein isolate Assumptions: processing and application of protein isolates is comparable
Life Cycle Inventory	Primary production data (e.g., energy and material flows, equipment, direct emissions) Secondary LCI data (e.g., life cycle inventory of material and energy supply)	Secondary LCI data (former project results, literature, ecoinvent)
Life Cycle Impact Assessment	Screening categories: Climate change, water footprint, land use, and primary energy demand Equal weighting of LCIA categories	Climate change, extended by farm gate price
Interpretation	Equipment, infrastructure, and transports have less impact, could be neglected for screening purposes Sensitivity analyses needed to cope with uncertainties Recommendations from an LCA perspective were iteratively applied during scale-up, allowing for comparative assessment to conventional fish feed pellets	"Ancient crops" (lentils) reveals high ecological benefits, however higher costs Highest impact is due to farming activities, thus R&D activities need to focus on optimization of the agricultural phase and utilization of waste streams (use as fertilizer, substrate for fungi production etc.), i.e., reducing ecological and economic burdens by future allocation

of the waste streams used or produced have no economic value so far, i.e., are defined as "waste". Secondly, by allocating the whole ecological backpack to the desired product, a conservative or even "worst case" scenario is considered.

3.1 Case study 1: life cycle assessment of fish feed derived from plants and insect

The global demand for fish and meat is still growing (Chemnitz and Becheva 2021; FAO 2020). The importance of the impacts of agricultural practices on water and land use, climate change, and environmental degradation, such as eutrophication, and terrestrial and marine acidification, is well acknowledged and has been exhibited by many studies. In this context, within the last years, insects are repeatedly discussed as a future-oriented, sustainable source of protein for the food industry, as the ecological, economic, physiological, and ethical advantages outweigh those of meat. In aquacultural systems, insects are also gaining interest as feed to provide a sustainable alternative to the fishmeal paradox (Alfiko et al. 2021; Silva et al. 2009), whose production leads to high consumption of resources and negative environmental impacts. Reducing the proportion of fish protein in favor of insect proteins in combination with vegetable feed components has the potential to reduce environmental burdens (Zanten et al. 2014). Within the scope of the project discussed here, the fish feed was produced from *Hermetia illucens* larvae and *Lemna minor* in an inline recirculating aquaponics model for urban sites, optimized, and scaled up, which couples waste and environmental service concepts in one production system efficiently. *Lemna minor* is also used for other purposes, such as wastewater treatment (O'Neill et al. 2020), but we intended to use it as an active ingredient for a circular-based production system. At the same time, the value chain produces high-quality, market-accessible raw materials for the food and feed industry. All research activities were accompanied by LCA as well as cost analyses to measure and compare ecological and economic effects to finally result in sustainable alternatives (Goyal et al. 2021).

The analysis of aquafeed was carried out cradle-to-gate, i.e., from the cradle (exploration of the raw materials) to the production of the individual components for the manufacture and use of the compound feed. Here, the pellets produced are referred to as LH pellets, which were found to have a similar protein and fat content as conventional tilapia feed. The system boundary considered in this study is shown in Fig. 3. The energy utilized in this study was derived from a biogas plant that was installed near the container where the species were rearing. This filled in as a benefit according to the environmental impacts' perspective.

Data were collected mainly from the process engineers using designated surveys with questions regarding inputs (raw material, energy, equipment) and the outputs (products and by-products), while additional data were also considered from the composition datasheet (e.g., for disinfectants, fertilizer). For primary data, which was unavailable, information based on literature was used as a proxy. Life cycle inventory data were, if not available, substituted or modeled (retrosynthetic break-down (Ott et al. 2016)), if possible. To cope with uncertainties, we finally also included a sensitivity

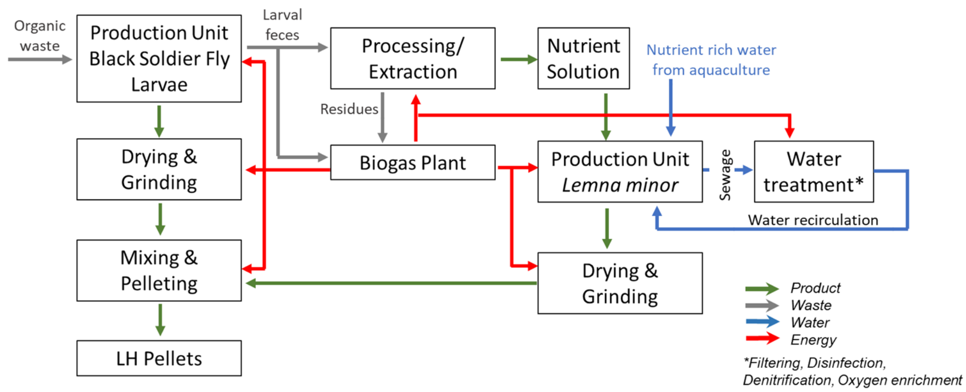

Fig. 3 Production scheme of case study 1. (See also (Goyal et al. 2021))

analysis, concentrating on the calculation of upper and lower limits, the "worst cases".

The modeling of the material and energy flows was carried out with the help of GaBi (developed by Sphera Solutions GmbH, Germany). By using the integrated Ecoinvent (version 3.5) database (Wernet et al. 2016), corresponding inventory data concerning the supply of raw materials, energy, or transport processes were integrated. The emission factors of all materials, energy sources, and transport processes are based on the Ecoinvent database. The impact assessment was carried out according to ReCiPe 2016 v1.1, utilizing midpoint indicators at the hierarchical level (Huijbregts et al. 2016). The time horizon of the impact assessment was 100 years. The ISO standards defined a functional unit (FU) as a quantified performance of a product system to be used as the reference unit in an LCA study. The use of mass-based FU was considered by Iribarren et al. 2012 for analysing the environmental footprint of marine aquafeed and also by Rustad 2016 to analyse insect meal which had the potential to replace fish meal. Hence, 1 kg LH pellets was considered as the FU for the LCA of fish feed production.

Figures 4 and 5 show the reduction potential of greenhouse gas (GHG) emissions for the supply of individual ingredients, i.e., energy and resources, for raw material production. Greenhouse Gas Potential, also referred to as Climate Change or Carbon Footprint, was chosen as it is the most prominent key objective for political and business-related decisions and can be seen as an important screening indicator of the environmental impact of products and processes. Additionally, as climate change is not reflecting the wholistic environmental profile of products and processes, we generally recommend selecting further impact categories for screening purposes as well, depending on the scope of the study. To give an example, in the context of the production of alternative feed, land use, primary energy demand, and water footprint could be of particular importance. The results to other impact categories can be found in (Goyal et al. 2021). Results are shown relatively, i.e., normalized to the worst-case value,

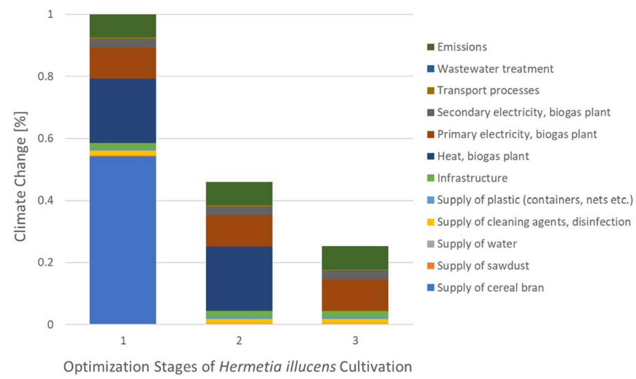

Fig. 4 Climate change potential during process optimization for Hermetia illucens breeding. Effects are normalized to the worst-case, i.e., starting point

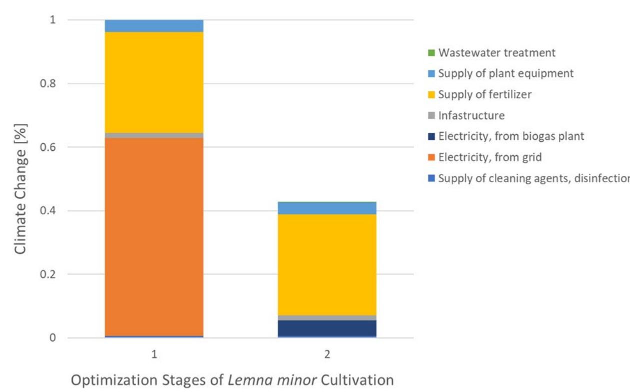

Fig. 5 Climate change potential during process optimization for Lemna minor breeding. Effects are normalized to the worst-case, i.e., starting point

which represents the starting point of the investigation. This prevents premature comparisons with other studies and conclusions, which can be the subject of later, more detailed analysis.

Figure 4 shows the development process of insect breeding. Firstly, insects were fed with cereal bran (Stage 1 in Fig. 4), affecting the ecological impact by more than 50%, and initiating to use of organic waste as feedstock (Stage 2 in Fig. 4), according to (EU) 2017/893) (European Commission 2017). Consequently, another driver could be identified, namely the energy consumption for maintaining the temperature inside the breeding container. The heat used is taken from a biogas plant which is installed in the vicinity of the container where insects are rearing. This is a clear advantage from the perspective of environmental impacts compared to the heat generated by non-renewable sources of energy Additionally, if the energy arising in the biogas plant would be considered as “waste energy” (as of now no dedicated purpose of it was foreseen at the manufacturing site), the environmental burden could be further reduced (Stage 3 in Fig. 4), revealing new ecological drivers such as cleaning agents, sawdust used for breeding, and electricity from the biogas plant. Hence, although optimization of 75% could be achieved, there is still potential for even further optimization, which will be considered during the upscaling stage.

Figure 5 shows the results for *Leman minor* process optimization through ecological screening. As for the rearing, a lot of technical equipment is needed, and these components (e.g., pipes, filters, trays, pumps, lamps, dehumidifiers) were listed as precisely as possible according to the material/equipment list given by the company which was establishing the rearing container. An initial evaluation based on the yield of *Lemna minor* culture obtained without optimization (Stage 1 in Fig. 5), however, showed inacceptable high ecological drawbacks not justifying the *Lemna minor* cultivation. Based on this, key performance criteria and recommendations were defined to approach at least ecological comparability to standard fish feed components. In the beginning, these key metrics could only be obtained by using artificial fertilizer instead of the use of feces from *Hermetia illucens* cultivation. As a consequence, and due to its significant ecological impact, the contribution analysis shows its greater impact. Its optimization, either by reducing its consumption (first trials were made empirically), recirculating the nutrient-rich water, or optimizing the feces composition, is an urgent subject of future investigation to reduce the overall environmental burdens of *Lemna minor* rearing. Secondly, electricity consumption was identified to be a main ecological driver, mainly attributable to air-conditioning, water pump circuits, and lighting. Also, in this case, the coupling to renewable resources, in this case, taken from the biogas plant (Stage 2 in Fig. 5), could result in a drastic change in the relative contribution of environmental impacts by a factor of 2.

Several recommendations and strategies could be derived for the production of sustainable and innovative raw materials for fish feed supply. Cultivation of *Hermetia illucens* and *Lemna minor* demand feed and energy, the main ecological drivers. The use of secondary raw materials can decrease the environmental burden by up to 75%. It is therefore important to perform LCA at the early development phase of a product or service to provide the stakeholders involved in the scale-up process with information regarding the influence of single parameters as well as the importance of using renewable energy and secondary raw materials for industrial production. Also, the impacts of the raw materials are enlightened by the successful implementation of LCA from the very beginning of the project.

The results concluded that fish feed made from Lemna minor and Hermetia illucens is potentially more sustainable than standard feed. The results were not comparable with literature because of the scale of the study but plant-based feed is more environmentally friendly than conventional feeds having high amount of fish remains or wild fish (Samuel-Fitwi et al. 2013; Smarason et al. 2017).

3.2 Case study 2: life cycle assessment of plant and fungal-based protein products for the sustainable food value chain

Animal-derived protein contributes significantly to the production of greenhouse gases, intensifies pressure on land use, and can have negative health consequences (Godfray et al. 2018; Song et al. 2016). In 2016, European Union used 39% of the total land area for agricultural production (Eurostat 2021) while the majority of agricultural land is used to produce livestock, either for feed production or grazing, with increasing competitive pressure from feedstock demand for non-food applications such as biofuels. The increasing demand for food proteins can be met by the utilization of proteins from alternative and new sources which includes under-explored legumes, protein crops, and fungi as well as side streams from food processing. In general, plant-based diets or meat substitutes often result in lower impacts on the environment than those with meat, see, e.g., (de Boer et al. 2014; Pimentel and Pimentel 2003; Westhoek et al. 2014). So far, existing LCA studies of food indicate the importance of side stream utilization on the overall sustainability (Nijdam et al. 2012; Scherhaufer et al. 2020; Souza Filho et al. 2019), but they also focus on the development of environmentally sustainable handling of different food side-flows in the future, as the processing and utilization of waste-stream do not automatically result in ecological benefits (Scherhaufer et al. 2020). Additionally, following the growing transition from animal-derived protein to plant-based protein, it is important to explore different plant-sourced proteins (e.g., lentil, soy, pea) and compare them in terms of their ecological, as well as their economic sustainability. As the price of food products is considered one of the key factors influencing consumers’ purchase behavior of environmentally sustainable foods (Vermeir et al. 2020), it is imperative to have a reasonable price for new products (Katt and Meixner 2020). Consequently, insights into the production costs of new products and the competing products are also needed (Rivera and Azapagic 2016).

The EU-funded Horizon 2020 project, Smart protein, aims to develop protein products from plants, including fava beans, lentils, chickpeas, and quinoa—with a focus on improving their structure, taste, and flavor, but also strongly focuses on sustainable agricultural processes, the utilization of by-products and residues as well as ingredients that are usually used for animal feed (Smart Protein 2020). In addition to plant-based proteins, microbial biomass proteins are created from edible fungi by upcycling side streams from pasta (pasta residues), bread (bread crusts), and beer production (spent yeast and malting rootlets). By using LCA, but also economic (life cycle costing) and stakeholder analyses, Smart Protein will be able to benchmark the findings against conventional protein food and agriculture approaches to evaluate its potential degree of competitiveness, sustainability, and resilience, and thus pave the way for enhanced protein production from plant and plant-based products and encourage their uptake, in Europe.

The determination of the ecological, but also the economic impact of plant protein products requires the implementation of upstream processes as well. Within Smart Protein new and organic agricultural practices and processing techniques will be developed (for which no or hardly any life cycle inventory data is yet available). Therefore, the collection of existing data was started to get a first insight into the sustainability of crops. In particular, lentils are of greater interest because lentil protein isolates have comparable protein content compared to dairy and soy-based milk products. It also possesses good sensory and techno-functional properties (Jeske et al. 2019). All these characteristics motivated the further investigation of the suitability of lentil protein isolate as a base material for a novel alternative to dairy or soy products.

A simplified LCA approach has been used to produce initial results. The goal was to explore the environmental benefits of using an alternative plant-based product. The considered data came from different literature sources as mentioned within because of its limited availability following a streamlined LCA approach. The advantage of such screening is that it highlights hotspots of environmental concerns which could be used for product development/commercialization (Todd et al. 1999). Berardy et al. determined the climate change potential of soy protein isolate at 20.2 kg CO_2 equivalents per kg of soy protein isolate (Berardy et al. 2015). Similarly, the climate change potential for soybeans and soymeal is about 0.6 kg CO_2 equivalents (per kg of soybeans) and 0.7 kg CO_2 equivalents (per kg of soymeal), respectively (Dalgaard et al. 2007). Braun et al. compared the ecological impact to other protein sources such as concentrated whey protein with 16 kg CO_2 equivalents per kg protein and skimmed milk powder with 23 kg CO_2 equivalents per kg protein (Braun et al. 2016). In contrast, the climate change potential for lentil protein isolate ranges between 3.5 and 4.2 kg CO_2 equivalents per kg isolate (Alonso-Miravalles et al. 2019). Looking at the costs, in general, it can be concluded that plant-based proteins could be a low-cost alternative to animal-based proteins in the food industry. The cost of cow milk protein is found to be higher than those of plant-based protein, such as soy (Li et al. 2019). Also, at the market price level, soy-based cheese is cheaper than milk-based cheese (Jeewanthi and Paik 2018). Lentils might also be another potentially valuable alternative for animal-based products. According toresearch (Chaudhary and Tremorin 2020), for example, the partial substitution of beef with Canadian lentils in a burger leads to a decrease in market price. The level of price reduction, however, depends on many factors such as geographic location, farming practice, and processing method (Khazaei et al. 2019).

Figure 6 presents the first comparable screening of environmental impacts and farm gate prices of lentils compared to soy and cow-milk-based protein supply. The ecological impact of lentil-based proteins, related to Climate Change potential, is promising compared to soy and milk-based proteins. This is not only relevant to climate change, but also to other LCA impact categories (LCIA) as well, as shown by Alonso-Miravalles et al. (2019). Their LCA study showed that the principal driver for the ecological impact of lentil

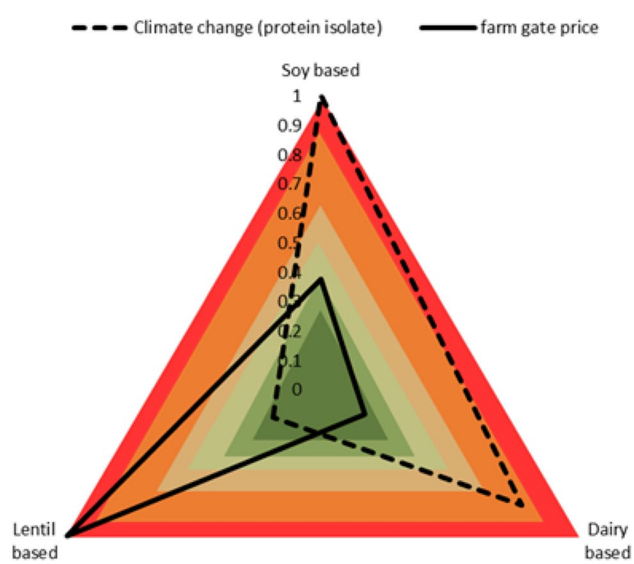

Fig. 6 Relative comparison of environmental effects for lentil, soy, and dairy-based protein isolates and farm gate prices for European lentils, soybeans, and cow milk (FAO 2021). Normalized to the worst-case results per impact category

protein isolates is the cultivation of the lentils, thus having ecological burdens, especially in the LCIA categories of Land Use and Aquatic Eutrophication. This first screening encourages to start the development of a lentil-based yogurt alternative, which could pose a viable way towards increasing human lentil consumption in Western countries, produced sustainably, regionally, or even locally (Boeck et al. 2021). Considering the similarity of the production process of yogurt from different protein isolates, one could expect that yogurt derived from lentil protein isolate might have a lower ecological burden than dairy- and soy-based products.

As a result of increased yields and acreage expansion, lentil production has increased globally since the 1950s. However, in Europe, the area under lentils declined sharply in the 1990s, with about 65% of the world's lentil production coming from Canada and India. Only in the last few years lentil cultivation has experienced a revival. The largest producers in Europe are Spain and France (FAO 2019). Due to limited own production and high import rates, the price is comparably high. Based on data from the Food and Agricultural Organization of the United Nations (FAO), farm gate prices for the year 2019 in Europe for soybeans were estimated to range between 284.1 and 592.7 $/tonne (FAO 2021). For cow milk and lentils, the farm gate price was, respectively, between 301.1 and 715.1 $/tonne and between 506.9 and 1799.4 $/tonne (FAO 2021). In 2019, soybeans were slightly less expensive in comparison to cow's milk, while European lentils were significantly more expensive (Fig. 6).

In the future, long-term optimization of agricultural practices is expected to result not only in a further reduction of the environmental impacts but also will affect the economic profile, thus reducing the high European farm gate prices of lentils as well.

This is currently addressed by the Smart Protein project: on the one hand, agricultural optimization activities are taking place, which is also strongly needed to start project-related ecological as well as the economic screening of lentil cultivation in comparison to benchmarks. Therefore, a project-specific survey was established and is currently being evaluated. On the other hand, the processing of lentils will result in side streams, which are foreseen to utilize as well to further reduce the environmental impact of lentil cultivation and isolate processing, but also lower the final lentil-based product costs. Allocation and sensitivity analyses will be then performed accordingly.

4 Conclusions

LCA is an established environmental tool that accomplishes an incorporated evaluation of the environmental impacts of alternative products/processes. As a methodology to assess ecological performance, it is known to be complicated, as its full framework requires extensive data, a prerequisite that cannot be met during the R&D stage. However, this paper underlines the importance of performing LCA at an early phase of product and process development as illustrated by two case studies in the food and feed sector.

Within case study 1, the researchers' scope was the production of fish feed using insects and aquatic plants in a developed and optimized recirculating aquaponics model. The outcomes of this study showed that fish feed derived from *Hermetia illucens* and *Lemna minor* might have the possibility to be more environmentally friendly than standard feed if the findings from the ecological screening would be implemented in the further development and scale-up. It is important to notice that the correlation here addresses the impacts of the task on a pilot scale. Different improvement possibilities were shown, which are fundamental for the wide scope execution of the two species rearing just as their processing up to the fish feed pellets. A more detailed explanation could be found in (Goyal et al. 2021).

Case study 2 deals with the development of plant-based dairy foods, whose proteins are extracted from plants like lentils, chickpeas or fava beans. The activities within the framework of the associated project are currently embedded in the early development stage, for which the application and adaption of LCA shall enlighten a path for further development towards industry-scale production. So far, a screening took place by means of a single impact category, as therefore the data availability and comparability to literature studies was well given. As the farming phase is expected to be environmentally driving the ecological profile of plant-based products, see also Ritchie and Roser 2021, optimization of farming activities will be exploited to holistically study the influence of farming practices, supplemented by theoretical simulation to cope with the uncertainties of the field trial experiments. The simulation model interacts with the plant species and different environmental conditions to recommend a promising production system. Project-related LCA results will be published in due time.

As a consequence, to accompany the development of new products by environmental assessment approaches, the LCA practitioner and all relevant stakeholders have to be aware that a simplified, broader, and more open approach instead of a traditional, holistic analysis has to be taken into account. Such analysis is being subject to large uncertainties and requires considerate assumptions that must be based on discussion, not on firm statements that are gratuitously presented as correct, (see also (Kunnari et al. 2009; Villares et al. 2017; van der Giesen et al. 2020; Beemsterboer et al. 2020a).

Moreover, there is a great need for background databases that can be used in modeling future technologies, as also recommended by van der Giesen et al. (van der Giesen et al.

2020). For an increased understanding of the importance and challenges of performing LCAs of emerging technologies and concepts, and for a growing life cycle inventory database and LCA result portfolio for future evaluation and comparative studies, the authors intend to encourage all researchers and practitioners engaged with LCA work to publish data regarding the application of LCA at the early stage of research and development of products and services.

Acknowledgements For the first case study, the authors gratefully acknowledge the financial support provided by the German Federal Ministry of Education and Research in the framework of the project "Lemna-Hermetia" ("KMU-innovativ" funding initiative, funding code 033RK048E). For the second case study, the project has received funding from the European Union`s Horizon 2020 research and innovation program under grant agreement No 862957 (Smart Protein).

Author contributions All authors contributed equally to the study conception and the structure of this article. The first draft of the manuscript was written by DO and SG and other co-authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

Declarations

Conflict of interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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