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Resource use efficiency: Developing a generic framework for protein production systems and its application on dairy and fish

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ABSTRACT

Resource use efficiency has become increasingly important as the global demand for natural resources continues to grow, necessitating innovative and sustainable utilization strategies. Despite the availability of tools to quantify resource use and environmental impacts, an integrated assessment of total resource use efficiency remains underdeveloped. Addressing this gap, particularly within the context of the protein transition from animal-based to plant-based sources, this work introduces a novel resource efficiency framework. This framework advances current environmental assessments by enabling the precise calculation of efficiency in protein production processes and process chains based on comprehensive resource utilization metrics. It uniquely incorporates the nature of process inputs, including their renewability and circularity, and supports both foreground and life cycle perspectives at the process and process chain levels. To demonstrate its applicability, two case studies—fish and dairy production systems—are evaluated using exergy and mass analyses.

1. Introduction

The concept of resource efficiency has garnered significant attention in the recent years due to the pressing need for sustainable use of natural resources. The United Nations estimates that by 2050, the world will require resources equivalent to almost three Earths to maintain current lifestyles (United Nations, 2022). This increasing demand requires a sustainable use of resources, especially within the food industry, which spans sectors including chemicals, agriculture, feed, food processing, trade, retail, and consumer goods (Perrot et al., 2016).

Rising incomes and populations drive the need for increased food production and a more efficient way to reach consumers. Transitioning to a food system that is actually environmentally sustainable requires fundamental changes in consumption habits as well as a re-model of production systems that rely heavily on energy, land, and water (Benton et al., 2021).

Animal agriculture, a significant part of the current protein supply, has well-documented contributions to climate change and other environmental impacts (Bajželj et al., 2014; Errickson et al., 2021; Ripple et al., 2014; Tilman and Clark, 2014; Tukker et al., 2011). Studies have suggested that reducing the livestock product consumption could mitigate these negative effects, by lowering greenhouse gas emissions (GHG) and land use associated with global agriculture (Bajželj et al., 2014; Poore and Nemecek, 2018; Tilman and Clark, 2014; Tukker et al., 2011). In light of these impacts, the next protein transition, i.e., shifting from animal to plant-based protein, is critical for enhancing the environmental sustainability of people's diets.

Within this context, the dairy industry, encompassing crop and animal agriculture as well as dairy processing, has a substantial environmental footprint, contributing to land degradation, water pollution, biodiversity loss, deforestation, and GHG emissions (Üçtuğ, 2019). Conversely, fish production, as an alternative to conventional meat, and generates lower GHGs emissions (Scarborough et al., 2014). The rising global fish consumption, from around 9.9 kg per capita in 1960 to 20 kg in 2020 (FAO, 2022a), highlights the potential of aquaculture to enhance global food security (Xu et al., 2022). However, the rapid growth of aquaculture raises concerns about resource limitations, particularly water, space, and feed, and the associated environmental

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impacts such as wastewater and solid waste production (Campanati et al., 2022).

Life Cycle Assessment (LCA) is a common methodology used to quantify the environmental impacts of food systems, in accordance with ISO 14044 standards (ISO 14044, 2006). LCA evaluates impacts from raw materials extraction through manufacturing, distribution, use and end-of-life treatment (Muralikrishna and Manickam, 2017). Despite the extensive information provided by LCAs, the assessment of resource efficiency is not encompassed, as it goes beyond the primary scope (Huysveld et al., 2015b). Exergy analysis, which quantifies the usefulness of resources, can complement LCA by providing a deeper evaluation of the environmental sustainability of food products and their supply chains. Furthermore, resource-intensive processes can be readily identified, enabling optimization strategies for resource consumption reduction (Apaiah et al., 2006).

To understand the full extent of resource consumption and its efficiency in protein production systems, these analyses should be conducted at both process and process chain levels, ideally integrating a life cycle perspective. Methods such as the Cumulative Exergy Extraction of the Natural Environment (CEENE) can quantify the extraction of natural resources taken from the natural environment, from a life cycle perspective and comprehensively account for resource consumption in one single, physically interpretable unit: exergy. Furthermore, it provides a robust and comprehensive approach to resource accounting in LCA, offering a valuable tool for evaluating the environmental sustainability of products and services. By considering the exergy extraction from the natural environment, CEENE highlights the true cost of resource consumption and facilitates informed decision-making towards a more sustainable future (Dewulf et al., 2007). CEENE has been evaluated as the "most complete and advanced accounting method", deemed easily applicable and well recognized in the scientific community (Sala et al., 2019).

However, there are essential limitations that need to be overcome, as addressed by Motte et al. (2022). First, resource efficiency analyses must account for the renewability of inputs and distinguish them from non-renewable resources. Secondly, because methods like CEENE were developed for linear economies-considering only resources directly extracted from nature- there is a need to integrate circularity indicators that account for the exergy contained in non-dedicated inputs, i.e., inputs from secondary sources or other supply chains (Motte et al., 2022).

This work presents a comprehensive resource efficiency framework that addresses current limitations in evaluating resource utilization through exergy analysis, at process and process chain levels. By modifying the CEENE method and applying it, the framework categorizes inputs based on their sources, distinguishing between dedicated, non-dedicated (secondary sources that support circularity), and environmental inputs. The integration of circularity and renewability factors provides a novel and robust tool for assessing protein production processes, whether in traditional agriculture or innovative systems, within the context of a circular economy. This framework uniquely enhances resource efficiency analysis by explicitly incorporating renewability and circularity, allowing for a more nuanced evaluation of food production systems. It offers a comprehensive assessment that not only aids process engineers in optimizing individual processes but also supports decision-makers by providing insights at the process chain level. The framework's applicability is demonstrated through two case studies—dairy and fish production—showing its relevance across diverse production systems. These cases are analyzed from a foreground perspective, and a life cycle perspective.

By building upon and extending the CEENE method, this innovative approach overcomes limitations in existing resource accounting methods and responds to the growing need for sustainable food production practices.

2. Materials and methods

2.1. Establishing a resource efficiency framework for protein production

To develop a resource efficiency framework, it is essential to define the key resources that need to be accounted for. The proposed framework enables users to calculate the efficiency of resource utilization for a chosen resource, aligning with the objectives outlined in the previous section.

Typically, a supply chain consists of several stages: raw materials production, product manufacturing and processing, distribution and sales, the use phase, and final disposal. For the purposes of this work, these stages have been renamed as follows: (agricultural) raw materials production, protein production, further processing, distribution and retail, use, and waste treatment. Although agri-food systems produce a variety of food commodities, this framework specifically evaluates protein-rich products, such as meat, dairy and their alternatives, which are commonly consumed for their protein content.

The efficiency framework is illustrated in Fig. 1. The foreground system includes the following processes: (agricultural) raw materials production (A), protein production (B), and further processing (C).

Each stage of the process involves inputs categorized into three main types, shown in Fig. 1: industrial dedicated inputs, industrial non-dedicated inputs, and environment inputs. Industrial dedicated inputs consist of materials or flows specifically produced for the supply chains, such as chemical fertilizers for crop production. Industrial non-dedicated inputs include co-products or by-products from other supply chains, such as sugar beet pressed pulp used in livestock feed. Environment inputs comprise materials, energy, or land resources directly taken from or released into the environment, which are considered in life cycle impact assessments (LCIA) associated to characterization factors, to estimate the impact of a given unit of a flow (Edelen et al., 2018). Essentially, environment inputs are converted into materials for the supply chain within the Technosphere, i.e., the realm of technology.

Process outputs are also depicted in Fig. 1 and are categorized as main products, co-/by-products, wastes, and emissions. Main product flows proceed to the subsequent supply chain step, while co-/by-products are assumed to go to post-processing plants. Waste from any stage in the supply chain is assumed to be directed to waste treatment facilities, and emissions are released into the environment.

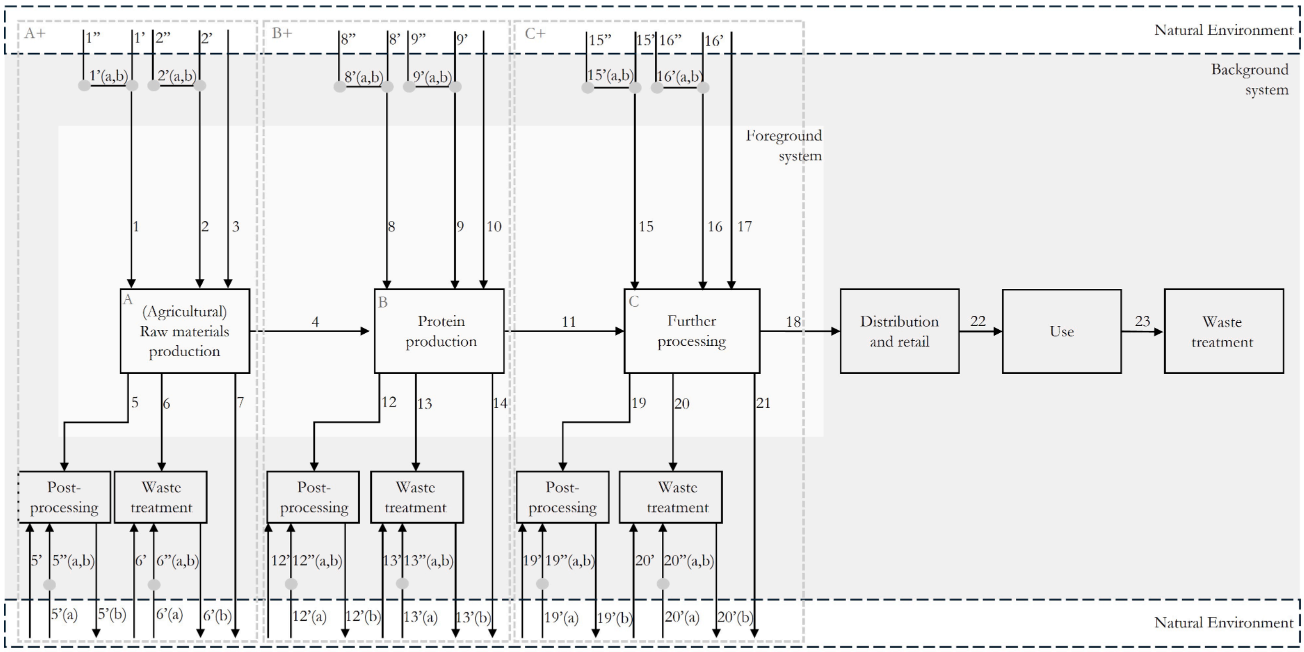
The background system considers all supporting processes and materials included in the study, such as the manufacturing of inputs, post-processing of co-/by-products, and waste treatment. The flows in this system can be documented using existing market data or data from LCA databases.

2.2. Levels and perspectives of analysis

The established framework offers flexibility in analysis at various levels and perspectives, as described in Table 1. The foreground perspective provides insight into the efficiency of processes A, B, and C, as well as the process chain A → C, modelled for each case study, as depicted in the light grey box in Fig. 1.

The life cycle perspective includes all foreground processes and their associated background systems, denoted by $\mathbf{A^+}$, $\mathbf{B^+}$ and $\mathbf{C^+}$ in Fig. 1. This perspective allows for the inclusion of all the natural resources extracted from nature at each stage of the product's life cycle and its process chain $\mathbf{A^+} \rightarrow \mathbf{C^+}$. In terms of levels, a process-level analysis considers processes A, A+, B, B+, C, and C+ as independent units, each assessed with its inputs and outputs. This level of assessment supports process engineering players in designing, operating, and optimizing these stages individually.

Furthermore, an overview of efficiency at the process chain level—integrating and calculating the resource use of all processes as one, represented by A → C and A+ → C+ in Fig. 1—provides advantages for higher-level divisions in the industry. Managers can utilize the



Unit processes A, B, C:
1, 8, 15. Industrial dedicated inputs for A, B, C
1', 8', 15'. Environment's inputs to manufacture **1, 8, 15**
1'(a), 8'(a), 15'(a). Industrial dedicated inputs for the manufacture of **1, 8, 15**
1'(b), 8'(b), 15'(b). Industrial non-dedicated inputs for the manufacture of **1, 8, 15**
1'', 8'', 15''. Environment's inputs to manufacture **1'(a,b), 8'(a,b), 15'(a,b)**
2, 9, 16. Industrial non-dedicated inputs for A, B, C
2', 9', 16'. Environment's inputs to manufacture **2, 9, 16**
2'(a), 9'(a), 16'(a). Industrial dedicated inputs for the manufacture of **2, 9, 16**
2'(b), 9'(b), 16'(b). Industrial non-dedicated inputs for the manufacture of **2, 9, 16**
2'', 9'', 16''. Environment's inputs to manufacture **2'(a,b), 9'(a,b), 16'(a,b)**
3, 10, 17. Environment's inputs for A, B, C
4, 11, 18. Main product from A, B, C
5, 12, 19. Co-products from A, B, C
6, 13, 20. Waste output from A, B, C
7, 14, 21. Emissions to environment from A, B, C

Post processing:
5', 12', 19'. Environment's inputs
5''(a), 12''(a), 19''(a). Industrial dedicated inputs
5''(b), 12''(b), 19''(b). Industrial non-dedicated inputs
5'(a), 12'(a), 19'(a). Environment's inputs to manufacture **5''(a,b), 12''(a,b), 19''(a,b)**
5'(b), 12'(b), 19'(b). Emissions to environment

Waste treatment:
6', 13', 20'. Environment's inputs
6''(a), 13''(a), 20''(a). Industrial dedicated inputs
6''(b), 13''(b), 20''(b). Industrial non-dedicated inputs
6'(a), 13'(a), 20'(a). Environment's inputs to manufacture **6''(a,b), 13''(a,b), 20''(a,b)**
6'(b), 13'(b), 20'(b). Emissions to environment

22. Ready-to-cook products from distributors and retailers
23. Wastes from consumers

Fig. 1. Resource efficiency framework to produce agriculture-based proteins and alternative proteins.

Table 1
Levels of analysis and their perspectives permitted by the efficiency framework.

	Perspectives	
Levels	Foreground	Life cycle
Process	A	A^+
	B	B^+
	C	C^+
Process chain	A → C	$A^+ \rightarrow C^+$

framework to ensure their process chains align with long-term environmental goals, maximize profit, and minimize inefficiencies. For example, a mass balance analysis of the process chain can facilitate appropriate material allocation to finished products and the identification of losses.

2.3. Resource use indicators

To assess the efficiency of protein production systems, various resource use indicators can be selected. For example, the alteration of nutrient flows, such as nitrogen, within global livestock supply chains due to the use of synthetic fertilizers and manure management (Uwizeye et al., 2020) could be studied by using a substance flow analysis (SFA) within the framework. SFAs evaluate inflows, outflows, and stocks (Loiseau et al., 2012), shedding light on potential losses. Conversely, in aquaculture systems, the cumulative energy use associated with feed production is a significant driver for climate change (Bohnes et al., 2019), suggesting that assessing the efficiency of various resources, including nutrients and energy, could be relevant indicators for evaluation within this framework.

For the selected case studies, two resources, namely mass and exergy, have been assessed for their use and efficiency. A systematic assessment of mass flows, such as material flow analysis (MFA), provides valuable insights for decision-makers regarding resource management (Brunner and Rechberger, 2016). MFA allows for the identification of material losses, efficiency, and usage rates for specific processes. In environmental engineering and management applications, MFAs have proven to be useful, supporting decision makers in the design of control strategies, nutrient management, soil-monitoring programs, and waste management. Additionally, the balance of the industrial input and output to natural ecosystems capacity is a key basic design principles of industrial ecology in which MFAs can be applied (Brunner and Rechberger, 2016).

Exergy analysis, on the other hand, quantifies the maximum useful work a thermodynamic system can produce when it equilibrates with its surroundings, through reversible processes (Dewulf et al., 2008). Unlike energy, which accounts for all energy flows regardless of their potential for work, exergy is considered a more suitable indicator for assessing resource utilization impacts. Exergy analysis measures the usefulness of energy and can aid in technology development by serving as a tool for assessing technical efficiency (Dewulf et al., 2008).

The comprehensive LCIA method $CEENE_{v2007}$, developed by Dewulf et al. (2007) and further modified by Alvarenga et al. (2013) referred to as $CEENE_{v2013}$, was used. This method quantifies the exergy withdrawn from natural ecosystems (Dewulf et al., 2007) and accounts for various resources, including renewable, fossil, nuclear, metal, mineral, water, land, and atmospheric resources, enabling assessment at both process and process chain levels.

Land occupation, as a resource, was first introduced in thermodynamic-based resource accounting methods in the $CEENE_{v2007}$. While other methods focus on the exergy or energy content of harvested biomass (Huysveld et al., 2015a), they do not account for land occupation. Since its introduction, land occupation has been included in all subsequent CEENE versions. Additionally, land occupation has also been integrated into the Solar Energy Demand method described by Rugani et al. (2011). In these methods, this indicator has been characterized by the area and duration ($m^2 \times$ year) required for biomass production. Consequently, different characterization factors have been determined, as described in Huysveld et al. (2015a). The $CEENE_{v2007}$ method takes land occupation into account by considering 2% of the solar surface irradiance (expressed as MJ_{ex}/m^2 x yr) (Dewulf et al., 2007), while Alvarenga et al. (2013) measures it through the site-specific potential net primary production (NPP) adjusted by the exergy of local solar radiation. Finally, the SED method calculates land occupation as the ratio between the annual emergy budget to global land area, multiplied solar energy influx (MJ_{ex}/m^2 x yr).

In order to better address land resources, a version of the Cumulative Overall Resource Efficiency Assessment (COREA) framework, developed by Huysveld et al. (2015a), was applied. This overcomes shortcomings associated with $CEENE_{v2007}$ and $CEENE_{v2013}$. COREA considers the maximum and minimum efficiency of photosynthetic processes in plants, crucial for land resource assessment. Land resources are considered renewable in this context because their productivity is fundamentally linked to solar radiation onto the land, which is harnessed through land occupation. This use of land prevents the natural production of renewable biomass, which is also driven by solar energy. Solar radiation fuels the photosynthetic process, resulting in biomass production, and the exergy from this solar input is accounted for in the CEENE framework under the land resources category. This means that bio-productive land resources can be effectively included by accounting, in this analysis, for a theoretical efficiency of 4.8%, calculated based on the ultimate maximum conversion efficiency of C4 species under ideal conditions (Zhu et al., 2010). By integrating modifications proposed in this study to the COREA framework, the revised CEENE method aims to optimize human intervention without compromising the photosynthetic processes of ecosystems.

To apply the framework at the life cycle perspective, the LCIA method CEENE was used through the software SimaPro 9.4.0.2. Modifications to the data received to apply the framework described were made, including a recalculation of the flows to update it to the latest version of the LCA inventory database Ecoinvent v.3.8.

2.4. Selected set of equations

Standard equations have been considered to calculate resource efficiency at both process and process chain levels. For simplicity, the equations presented herein focus on exergy; however, calculations have also been conducted using mass as a unit. Table 2 summarizes the equations used for calculations across all levels and perspectives.

Table 2
Summary of equations applied in the resource efficiency framework.

Levels	Equations	Perspectives: Foreground	Perspectives: Life cycle
Process: A, B, C, A^+, B^+, C^+	Universal efficiency	Eq. (1)	Eq. (2)
Process chain: A → C, $A^+ \to C^+$	Product(s) & co-/by-product efficiency	Eq. (3)	Eq. (4)
	Product efficiency	Eq. (5)	Eq. (6)
	Waste and emissions ratio	Eq. (7)	Eq. (8)
	Recovery indicator	Eq. (9)	Eq. (10)
	Renewability factor	NA[a]	Eq. (11)

[a] Not applicable.

From the foreground perspective, the universal efficiency of the process, η_u, represents the ratio between the total output exergy $(Ex_{outputs})$ and the total input exergy (Ex_{inputs}), as defined by Eq. (1) (Genc, 2018). Meanwhile, from the life cycle perspective, efficiencies of A^+, B^+, C^+, and the process chain $A^+ \to C^+$, can be determined using Eq. (2), where CEENE refers to the total exergy extracted from the natural environment over the entire life cycle.

$$\eta_u(\%) = \left(\sum Ex_{outputs} \Big/ \sum Ex_{inputs}\right) * 100 \quad (1)$$

$$\eta_{uLC}(\%) = \left(\sum Ex_{outputs} \Big/ CEENE\right) * 100 \quad (2)$$

$Ex_{outputs}$ considers the exergy embedded in the main product, co-/by-products, wastes and emissions. Eq. (3) represents the ratio between the exergy of useful products and the total exergy inputs (Romero and Linares, 2014), known as product and co-/by-product efficiency, $\eta'(\%)$. For simplicity, co-/by-products are denoted as co-products in equations. This ratio provides an understanding of how efficiently resources are being utilized to produce the outputs.

From the life cycle perspective, the concept of Cumulative Degree of Perfection (CDP) introduced by Szargut et al. (1987), is used. CDP is defined as the ratio between the exergy contained in the main product and co-/by-products and the cumulative exergy of the entire supply chain, as shown in Eq. (4). This measurement provides a comprehensive view of the efficiency of the entire production system, considering all stages from raw material extraction to final product.

$$\eta'(\%) = \left(Ex_{main\ product} + Ex_{co-products}\right) \Big/ \sum Ex_{inputs} * 100 \quad (3)$$

$$CDP_{pcp}(\%) = \left(Ex_{main\ product} + Ex_{co-products}\right) / CEENE * 100 \quad (4)$$

To calculate the efficiency with which a process converts inputs exclusively into the main desired output, the product efficiency, η, is measured (Huysveld et al., 2015a). This efficiency is defined as the ratio of exergy between the main product and the total inputs, as shown in Eq. (5).. At the life cycle level, this efficiency is expressed by the CDP of the main product, as shown in Eq. (6) (Szargut et al., 1987).

$$\eta(\%) = Ex_{main\ product} \Big/ \sum Ex_{inputs} * 100 \quad (5)$$

$$CDP_p(\%) = Ex_{main\ product} / CEENE * 100 \quad (6)$$

The quantification of the exergy or mass of resources utilized in the process that are exiting the system as emissions and waste is depicted in Eqs. (7) and 8, from a foreground and life cycle perspective, respectively.

$$WR(\%) = \left(Ex_{wastes} + Ex_{emissions}\right) \Big/ \sum Ex_{inputs} * 100 \quad (7)$$

$$WR_{LC}(\%) = \left(Ex_{wastes} + Ex_{emissions}\right) / CEENE * 100 \quad (8)$$

Additionally, to address the circularity and renewability of resources and processes, two indicators based on the research by Motte et al. (2022) have been included in the framework. The recovery indicator (RI) provides an overview of the circularity of the system. This indicator is defined for the foreground and life cycle perspectives by Eqs. (9) and 10, respectively.

$$RI(\%) = Ex_{non-dedicated\ inputs} \Big/ \sum Ex_{inputs} * 100 \quad (9)$$

$$RI_{LC}(\%) = Ex_{non-dedicated\ inputs} / CEENE * 100 \quad (10)$$

The utilization of renewable resources in a process helps mitigate impacts related to the dependency on finite fossil reserves (Motte et al., 2022). In resource efficiency analyses, a renewability factor can quantify this. This was first proposed by Dewulf et al. (2000) as the parameter α, i.e. the fraction of renewable exergy consumption with respect to the total exergy consumption. This parameter was later coupled to the CEENE method by Motte et al. (2022), and is shown in Eq. (11):

$$RF(\%) = CEENE_{renewables}/CEENE \ * 100 \quad (11)$$

The renewability factor quantifies the extent to which renewable resources are used in the process, offering insight into the sustainability of resource consumption by distinguishing between renewable and non-renewable inputs. In this evaluation, several categories from the CEENE method are considered renewable, including abiotic renewable resources, water resources, land and biotic resources, as well as atmospheric resources (Motte et al., 2022). By accounting for these diverse categories, the method ensures a comprehensive assessment of the renewable inputs involved in protein production.

2.5. Case studies

Two production processes delivering high-quality protein-rich foods have been selected. Fish and dairy production often involves complex, multi-service models that integrate various aspects of the agricultural value chain. This complexity provides numerous opportunities to apply and test the proposed framework, which could provide insights applicable to other agricultural or food systems. By selecting fish and dairy production for this research, the intersection of resource efficiency, circularity, and sustainable practices can be explored. The comparison of thermodynamic efficiency of resource use in aquatic systems versus terrestrial systems might reveal unique insights into the different requirements of land-based and water-based sustainable protein production. Additionally, the availability of different well-studied case data in both industries allows for thorough testing and validation of the framework.

2.5.1. Dairy farming case study

Huysveld et al. (2015b) conducted an exergy analysis and an exergy life cycle assessment using the $CEENE_{V2013}$ methodology on a confinement-based dairy farm in Flanders. The system boundaries include all activities from cradle to farm gate, with the functional unit defined as 1 kg of fat-and-protein-corrected milk (FPCM). For detailed inventory data, refer to Huysveld et al. (2015b). The exergy data used to validate the framework presented in this study was sourced from the aforementioned authors.

Based on data availability, the dairy farm system was divided into two main processes: A and B (Fig. 1).

Process A: Roughage Production

This process involves the production of grass and maize silage under rainfed conditions. Industrial dedicated inputs include fuel for crop production, infrastructure, seeds, fertilizers, water, and protection products, among others. Industrial non-dedicated inputs include liquid and solid manure spread on the fields. The main environmental input is land. The primary output from Process A is crops, which are then used in Process B. Co-products are minimal and emissions include water and gaseous emissions such as CO_2 and CH_4.

Process B: Cattle Husbandry

This process integrates sub-processes such as housing, feeding, milking, and manure storage. Dedicated inputs include water supply, electricity, additional maize silage purchased by the farmer, and purchased concentrates. Industrial non-dedicated inputs include co-products such as pressed sugar beet pulp. Environmental inputs primarily include land for stables and silos. The main product is milk sold to the processing factory, while co-/by-products include culled cattle and manure. Wastes include wastewater and discarded milk, with emissions including CO_2, CH_4, and water.

2.5.2. Fish farming case study

The second case study involves one of the leading Vietnamese exporters of Pangasius food products, initially assessed by Huysveld et al. (2013) and later studied by Nhu et al. (2015). Data for this study was provided by the named authors.

The foreground system comprises processes A, B, and C:

Process A: Feed production

This process occurs at the company's feed mill, which consists of nine steps: dosing, milling, mixing, cooking, extruding, drying, cooling, coating, and packaging (Huysveld et al., 2013). Industrial dedicated inputs include additives (e.g., vitamins), electricity, and water. Non-dedicated inputs include fish meal and wheat bran. The main environmental input is land used for feed production. The primary output is feed pellets destined for Process B. Co-/by-products include ashes provided to local farmers, and emissions include boiler outputs such as water, CO_2, NO_x, and SO_2.

Process B: Pangasius Farming

This process includes the company's four farming sites. Dedicated inputs include fingerlings, electricity, and additives. Non-dedicated inputs include secondary products such as salt from other farms, and environmental inputs include freshwater and land use. The primary output is Pangasius fish, with co-/by-products including dead fish and sludge. Emissions at this stage include wastewater released to the river and gases such as CO_2.

Process C: Fish Processing

This process involves industrial dedicated inputs such as chemicals, water, living fish, and packaging materials. Outputs include processed fish, with co-products such as fish heads, bones, fins, skins, and other parts. Wastewater is also quantified as waste from this process.

Overall, this comprehensive framework allows for the systematic analysis and optimization of resource use and efficiency across different stages of production in both dairy farming and fish farming systems.

3. Results and discussion

3.1. Exergy-based framework for food production

Although exergy-based frameworks for assessing protein production systems are relatively uncommon, Zisopoulos et al. (2017) developed a conceptual exergy-based framework, building upon the one presented in Hák et al. (2016), specifically for the agro-food sector. This framework is designed to assess, monitor, and improve resource efficiency with the goal of contributing to the 12th Sustainable Development Goal (SDG): ensuring sustainable consumption and production patterns. The core focus of this framework is on quantifying exergy consumption and identifying opportunities for resource efficiency improvement.

The framework presented in this study builds upon these foundations, addressing the need for a systematic method to quantify resource use efficiency in food production. It expands on existing work in both scope and the integration of specific factors into the analysis. While both frameworks utilize exergy analysis as a core methodology, the framework in this study advances beyond the previous models by explicitly incorporating considerations of circularity and renewability. This extension not only broadens the scope but also enhances the framework's ability to evaluate resource flows more holistically. One of the key innovations in this framework is its categorization of inputs based on their source—whether they are dedicated, non-dedicated, or environmental inputs. This differentiation provides a more nuanced understanding of resource flows, enabling a clearer identification of the origins and potential impacts of these inputs on overall resource efficiency and sustainability. In particular, distinguishing between dedicated and non-dedicated inputs proves crucial for evaluating the circularity of the system, as it allows for a more accurate assessment of resource loops and waste minimization.

Additionally, the incorporation of environmental inputs ties the framework more closely to broader environmental impact assessments. By highlighting the extraction of direct resources from ecosystems, the framework emphasizes the importance of minimizing the environmental burden associated with production processes.

3.2. Process level assessment

As previously outlined, the dairy farm system was divided into two primary stages: A and B. Similarly, for the Pangasius case study, stages A and B were included, with an additional stage, C, incorporated due to data availability.

For process A, the functional units were defined as 1 kg FPCM sold for the dairy case, and one ton of feed produced for the fish case. The efficiencies for this stage in both systems are presented in Table 3. Universal efficiency, η_u, was 11.4% for the dairy system and 88.1% for the fish system from a foreground perspective, and 14.1% and 33.4% from a life cycle perspective, respectively. The foreground product and co-/by-product efficiency η', was 11.5% for the dairy system and 87.4% for the fish system, while the cumulative degree of perfection for the product and co-/by-product, CDP_{pcp}(%), from a life cycle perspective was 14.1% for the dairy system and 33.1% for the fish system.

In the dairy case, the results were predominantly influenced by the environment's inputs, which accounted for 93.5% of the total inputs in terms of exergy. This is attributed to the nature of agricultural practices, which heavily rely on land use and solar energy. Specifically, solar radiation made the highest contribution within this category, consistent with findings by Huysveld et al. (2015b). Consequently, most of the exergy entering the system is dissipated. It is important to recognize that solar radiation is a renewable resource, which adds a significant renewability component to this step of the supply chain. However, the high dissipation rate of solar energy highlights the need for improved capture and utilization strategies in agricultural practices to enhance overall efficiency. The renewability factor was 98% and detailed in Table 4, where land resources accounted for 97.3% of the inputs, followed by renewable resources and water resources, contributing 0.5% and 0.2%, respectively.

Regarding mass efficiency of process A in the dairy system, the mass-based product and product and co-/by-product efficiency, η', was 0.7%. This low efficiency is largely because most of the water not contained in the crops (i.e., water transpired by the plants) represents a significant share of the output. This explains the high mass-based waste ratio, *WR*, of 98.2%. Additional information on mass efficiencies can be found in the supplementary information (SI).

Table 3
Efficiencies in % calculated for process A and B of both systems, from the foreground perspective and life cycle perspective. Additionally, process C for the fish system is included from both perspectives.

Dairy				Fish			
A		A$^+$		A		A$^+$	
η_u	11.4	$\eta_{u\ LC}$	14.1	η_u	88.1	$\eta_{u\ LC}$	33.4
η'	11.5	CDP_{pcp}	14.1	η'	87.4	CDP_{pcp}	33.1
η	11.4	CDP_p	14.0	η	87.2	CDP_p	33.1
B		B$^+$		B		B$^+$	
η_u	50.6	$\eta_{u\ LC}$	20.1	η_u	83.4	$\eta_{u\ LC}$	54.5
η'	43.8	CDP_{pcp}	17.6	η'	13.6	CDP_{pcp}	8.7
η	13.6	CDP_p	5.5	η	12.1	CDP_p	8.0
				C		C$^+$	
				η_u	51.9	$\eta_{u\ LC}$	1.7
				η'	47.2	CDP_{pcp}	8.0
				η	6.8	CDP_p	1.2

Table 4
Share of renewable resources utilization in process A and B of both the dairy system and the fish system.

	Dairy		Fish	
	A$^+$	B$^+$	A$^+$	B$^+$
Land resources (%)	97.3	86.4	59.4	21.9
Water resources (%)	0.2	1.0	19.8	66.0
Renewable resources (%)	0.5	0.3	6.1	0.6

A similar trend is observed in the analysis of the Pangasius stage A of the supply chain. Of the total CEENE, 59.4% of the resources are represented by land used for biomass production, as a significant amount of land is required to produce feed for aquaculture systems (Huysveld et al., 2013). Water resources account for 19.8%, and renewable resources contribute 6.1%. Consequently, the total renewability factor for the fish case study is 85.3%.

In contrast, several differences are evident when considering the foreground system and its circularity. The process A exergy based *RI* for the dairy case was 5.8%, significantly lower than the 98.5% calculated for the fish case study. This disparity is explained by the nature and origin of the inputs for these processes, as shown in Table 5. The high *RI* proves that the fish system has a greater use of industrial non-dedicated inputs, which enhances circularity by incorporating by-products and co-products from other processes.

A similar result is found when analyzing material circularity. The mas-based *RI* for the Pangasius system was 81.8%, indicating a more efficient use of materials compared to the dairy production system. These findings suggest that the aquaculture system not only utilizes renewable resources more effectively but also has superior circularity and resource efficiency. More details on mass-based circularity are available in the supplementary information (SI).

For the dairy system's process A, as observed in as observed in Table 5, over 90% of the inputs' exergy is derived from environmental sources, primarily solar energy, highlighting the heavy reliance that agricultural practices have on natural resources, as previously explained. In contrast, the fish system shows a marked difference in input's structure. Moreover, only 1.5% of the exergy is due to industrial dedicated inputs for feed production, while 98.5% comes from inputs categorized as co-products or by-products from other industries. Examples of these secondary inputs include rice bran, soybean meal, poultry meal, and fish oil. Finally, a negligible amount is coming from the environment.

The categorization of these products as secondary inputs from other industries raises important discussions about the boundaries between dedicated and non-dedicated inputs. For instance, soybean meal, although a co-product of soybean oil extraction, is widely utilized as a protein supplement in animal feed and plays a crucial role in livestock and fish production globally (Dalgaard et al., 2008). As demand for soybean meal increases, so does the production of soybean oil. Additionally, the definitions of by-product, co-product, residues, and waste are not straightforward, leading to varying rationales when assigning environmental impacts or burdens to these flows in LCA (Olofsson and Börjesson, 2018). Therefore, environmental assessments must consider the type of allocation used to understand how the market dynamics are

Table 5
Share of exergy contained in each type of input relative to total exergy extracted from the natural ecosystem, for both case studies, in process A.

Input source	Dairy	Fish
Industrial dedicated (%)	0.7	1.5
Industrial non-dedicated (%)	5.8	98.5
Environment (%)	93.5	0.0

affected by the production of primary products. The European Commission has proposed the Circular Footprint Formula to address multi-functionality, aiming to incorporate a consequential LCA perspective by considering the market effects of secondary materials used in production processes (European Commission, 2018; Schrijvers et al., 2021). This formula responds to the need for a consistent method of allocating environmental burdens.

For process B, Table 3 shows the efficiency calculations for both case studies. The functional units were defined as 1 kg FPCM sold for the dairy system and 1-tonne live-weight Pangasius fish at the farm gate for the fish system. This comparison highlights the significant differences in resource utilization and efficiency between the two production systems.

As stated, the universal efficiency from the foreground perspective was 50.6% for the dairy system and 83.4% for the fish system. When viewed from a life cycle perspective, these efficiencies were 20.3% for the dairy and 54.5% for the fish. In the case of dairy, the production of co-/by-products, primarily manure, significantly enhances the exergetic efficiency of the process. Manure, when reapplied to fields, recycles nutrients, and reduces the need for synthetic fertilizers, thus improving overall resource efficiency. This highlights the importance of reusing materials to optimize overall resource use. For fish, although the increase in efficiency is not as pronounced as for the dairy case, it still benefits from the utilization of by-products. Dead fish, for instance, are often used by local farmers, contributing to nutrient cycling and the reduction of waste. While it can be observed that the impact of this is lower than the manure recycling in dairy farming, still contributes positively to the system's efficiency. These findings prove the importance of integrating renewable resource use and material reuse into both agricultural and aquacultural practices. The data suggests that while the fish system shows higher initial efficiency, the dairy system's ability to recycle manure offers an opportunity for improvement.

Table 4 also details the renewable resources used for process B of the dairy and the Pangasius, respectively. Results indicate that stage B of the dairy farm has a renewability factor of 87.7%. This high renewability is primarily due to the significant share of land resources related to the feed supply, which account for 86.4% of the exergy extracted from the natural ecosystem. In addition, water resources contribute marginally with roughly 1% and renewable resources add another 0.3% to the total exergy input.

For Pangasius, 66.0% of the total exergy extracted from the natural ecosystem is attributed to the use of water resources. This is followed by 21.9% from land resources and 0.6% from renewable resources. The reliance on water resources is due to the farm's access to it from the Mekong River's distributaries. Water transportation is done either by pumping or natural tidal forces (Huysveld et al., 2013). Additionally, the frequent renewal of water in fishponds is necessary to maintain suitable conditions for fish farming. The value for water resources utilization differs significantly from the one reported by Huysveld et al. (2013), in which water resources accounted for 31% of the total CEENE. The variation can be explained by the difference in characterization factors in the CEENE methods, particularly to land resources. In Huysveld et al. (2013), land resources contributed to more than 60% of the total CEENE, whereas in this study, they contributed to approximately 22%.

The extensive use of water resources in the Pangasius production process is reflected in the mass-based *WR* ratio, which amounts to 99.2%. This high value is a consequence of the substantial release of wastewater into the river, underscoring the need for efficient water management practices to minimize environmental impacts and increase the sustainability of fish farming.

The functional unit for the processing of the Pangasius in Vietnam is defined as 1 ton of fish fillet (dry matter) in packaging at the factory gate and its efficiencies are shown in Table 4. As observed, the efficiency of process C greatly increases when the co-products such as the head, bones, skin, and other parts are considered. Despite this improvement, the potential to enhance the efficiency of the process remains, particularly by reducing water consumption during the filleting and freezing stages. In addition, optimizing the use of packaging materials and electricity throughout the entire processing stage could further increase resource efficiency.

A detailed process-level assessment, as demonstrated, allows for the identification of specific opportunities to enhance sustainability. Given the increasing pressure on industries over the past decades to adopt more environmentally friendly practices, including waste and emission reduction (Pieragostini et al., 2012), this type of resource efficiency assessment tool proves invaluable for achieving these goals. By focusing on individual processes, stakeholders can identify areas for improvement and make the corresponding decisions to optimize wherever necessary.

3.3. Process chain level assessment

For the process chain level assessment, the functional unit for both case studies was redefined to be 100 g of protein. This has been determined to be contained in 3.3 kg of dairy milk and 0.693 kg of Pangasius fish. The system boundaries considered for both case studies are depicted in Fig. 2. To facilitate a direct comparison and due to data availability, only the first two stages of the production chain were included, specifically A→B and $A^+ \rightarrow B^+$.

The total **CEENE** per 100 g protein for dairy and fish amounted to 213.1 MJ and 154.1 MJ of exergy, respectively. The most significant differences in contributions to the total CEENE are in water resources, which represented 1.1% in the dairy process chain and 49.1% in the Pangasius process chain. As expected, land resources accounted for the majority in the dairy case (86.9%) compared to the fish case (35.6%).

The efficiencies calculated for both the foreground systems and life cycles of each case are shown in Table 6.

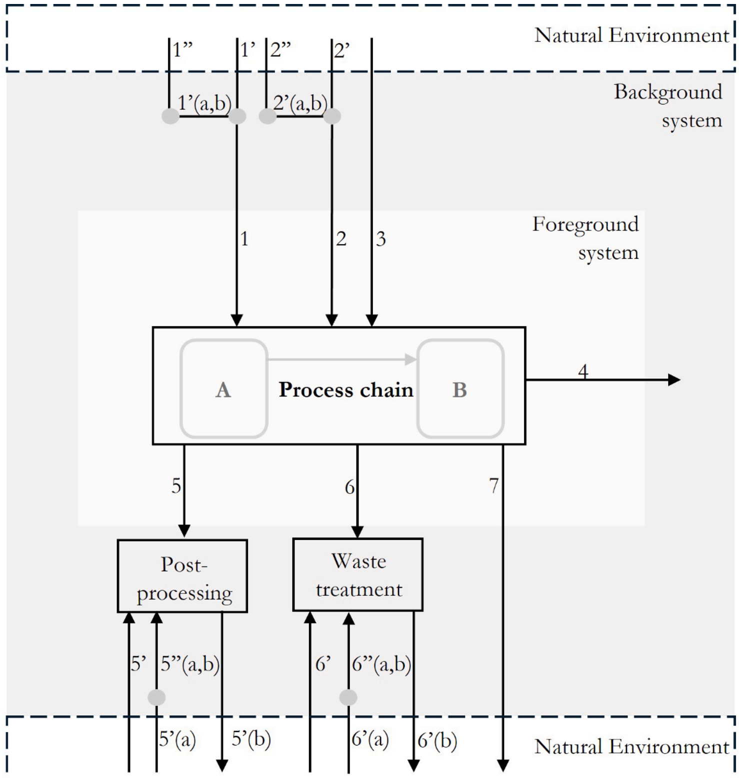
As observed, η_u, η' and η are higher in the Pangasius' A→B process chain. This is directly related to the amount of exergy derived from solar energy for feed production in the dairy process chain, where approximately 91% of the output exergy is dissipated. Since exergy destruction measures the degradation of resources, the performance of the dairy process chain could be improved by reducing it by increasing the efficiency of crops and simultaneously increasing the overall efficiency.

For the Pangasius example, there is still room for improvement in η' and η. Including the processing step can enhance the efficiency of converting inputs into useful products due to the exergy contained in the co-/by-products. Low efficiencies could be increased by optimizing electricity use and, notably, water consumption. The waste and emissions ratio, *WR*, for Pangasius was 67.4% and the WR_{LC} was 28.8% due to the water output, a contrast to the dairy system, where these values were 1.2% and 2.3%, respectively. Huysveld et al. (2013) proposed several options to increase the efficiency of water resource utilization, such as integrating filtering technologies, closing the water loop to control water quality, and other water recycling methods.

Because this work has suppressed the potential photosynthetic inefficiencies through the CEENE method, resource use efficiency can only be improved by human made systems. An alternative strategy for improving efficiency in crop production for both systems could involve precision agriculture (PA). PA employs advanced technologies to improve crop yields, agricultural productivity, product quality and resource-use efficiency while enhancing environmental sustainability (FAO, 2022b). Decision makers can benefit from these advancements to better manage agricultural processes, thus improving incomes and reducing the workload on farms. However, this study has not included economic assessment which could become inconvenient when applying some of these strategies. These solutions are particularly necessary from crop and livestock production, as well as for aquaculture and fisheries (FAO, 2022b).

3.4. The role of solar radiation

The use of different characterization factors to account for land



PROCESS CHAIN:
1. Industrial dedicated inputs
1'. Environment's inputs to manufacture n°1
2. Industrial non-dedicated inputs
2'. Environment's inputs to manufacture n°2
3. Environment's inputs
4. Main product from production process chain
5. Co-products
5'. Environment's inputs for post-processing
5'(a). Environment's inputs to manufacture n°5"(a,b)
5''(a). Industrial dedicated inputs for post-processing
5''(b). Industrial non-dedicated inputs for post-processing
5'(b). Emissions to environment from post-processing
6. Wastes
6'. Environment's inputs for waste treatment
6'(a). Environment's inputs to manufacture n°6"(a,b)
6''(a). Industrial dedicated inputs for waste treatment
6''(b). Industrial non-dedicated inputs for post-processing
6'(b). Emissions to environment from waste treatment
7. Emissions to environment from process chain

Fig. 2. System boundaries for process chain analysis.

Table 6
Efficiencies in % calculated for the processes' chains.

Dairy				**Fish**			
A→B		A^+→B^+		A→B		A^+→B^+	
η_u	8.9	$\eta_{u\ LC}$	16.7	η_u	80.4	$\eta_{u\ LC}$	34.3
η'	7.8	CDP_{pcp}	14.4	η'	13.0	CDP_{pcp}	5.6
η	2.4	CDP_p	4.5	η	11.5	CDP_p	5.0

occupation, as explained in Section 2.3, can significantly influence the outcomes of resource accounting. These varying approaches reflect different environmental perspectives and local conditions, which might lead to inconsistent or incomparable results, especially when evaluating land-based systems such as agriculture or forestry. For example, systems analyzed using net primary production may appear more or less resource-efficient than those assessed based on solar irradiance, depending on the location and productivity of the land. This difference could present challenges when comparing land use impacts across production systems, potentially leading to biased conclusions about sustainability and efficiency if the methods are not standardized. Thus, careful consideration is needed when comparing results across studies using different land occupation indicators.

For example, in the raw material production of the dairy system, when assuming 100% utilization of solar radiation on the farm, the foreground universal efficiency η_u drops to 0.6%, compared to 11.4% when using a photosynthetic conversion efficiency of 4.8%. This is because the total exergy from solar radiation amounted to 2012.9 MJ, making it the largest contributor in terms of inputs, as shown in Huysveld et al. (2015b).

Similarly, for process B in the dairy system, from a life cycle perspective, if the spatial differentiation factor for Belgium (26.9 MJ/m^2 x yr) from Alvarenga et al. (2013) is applied, the life cycle universal efficiency $\eta_{u\ LC}$, reaches 37.5%. However, using the approach described in this study, the efficiency drops to 20.1%. These discrepancies, observed across all efficiency calculations within the dairy and fish systems, illustrate how different methods for accounting for land occupation can significantly impact the results.

Zisopoulos et al. (2017) argues against including solar exergy and photosynthetic losses in exergy analyses of food production chains, reasoning that such inclusion may overwhelm the analysis by dwarfing the subsequent transformed exergy flow. In this study, the validity of this concern is demonstrated by quantifying the exergy content of solar radiation, assuming a photosynthetic efficiency of 4.8% and accounting for the total incoming solar radiation. These results show that incorporating solar exergy significantly alters the overall efficiency of the production process, as the sheer magnitude of solar radiation, compared to the transformed exergy, skews the efficiency metrics. This finding supports Zisopoulos et al. (2017) caution, as including such a vast, underutilized energy input complicates the assessment of downstream energy transformations, especially when modelled with different approaches, as previously mentioned. However, this also highlights a broader challenge in integrating renewable energy sources like solar radiation into exergy analyses—particularly for systems where photosynthesis plays a central role, as it creates an imbalance between resource inputs and system efficiency that may obscure other resource flows.

3.5. Uncertainty

Uncertainty is present throughout all stages of a life cycle assessment (LCA) and stems from various sources, such as variability, inaccuracies in measurements, data gaps, inventory data that might not be fully representative, decisions made by users regarding methods of assessment, and ones related to mathematical models (Mendoza et al., 2018).

In the exergy-based framework presented, uncertainty arises from several sources, reflecting the complexities of such analyses. These include uncertainties inherent to LCA, such as variability in data, and gaps in available information, all of which can impact the accuracy of the results, especially when carrying out comparative assessments as the one in this study. Specifically, in the context of the characterization factors for resources like land, as discussed in the previous section, there are uncertainties related to how land occupation is quantified and incorporated into thermodynamic assessments, which can and does influence comparative evaluations of different systems. Additionally, the extensive amount of data required for a thorough exergy analysis, especially across diverse resource types, introduces further uncertainty, particularly when data availability is limited or inconsistent. Practitioners should be mindful of these uncertainties when applying the framework. Nevertheless, exergy analysis tends to have lower uncertainties compared to other metrics, as it is based on well-established thermodynamic principles that provide a consistent and scientifically robust foundation for evaluating resource use efficiency.

To measure and account for uncertainty in the model, some of the most widely used approaches include Monte Carlo simulation, which demands a large number of simulations to achieve representative outcomes. Often amount used in literature are 1000 or 10,000 runs (Igos et al., 2019). These simulations provide insights into the range and likelihood of different outcomes. As for qualitative analysis, a method to estimate default standard deviations for flow data can be used in Ecoinvent. This is based on the characteristics of the flows and corresponding processes, which are then converted into uncertainty factors using the provided pedigree matrix (Ciroth, 2012). Furthermore, scenario analysis, such as the one carried out for land occupation characterization factors, explore how different methodological choices or normative assumptions (e.g., allocation methods, functional units) impact the results, capturing scenario uncertainty. In addition to the above mentioned methods, there are other ways to assess uncertainty. Regardless of the method chosen, incorporating uncertainty analysis is essential for obtaining a more accurate and reliable understanding of the models and their results, in order to improve the overall credibility of the assessment.

4. Conclusions and perspectives

From a life-cycle perspective, efficiencies differ between systems. For example, the CDP_{pcp} of the dairy system indicates higher resource use efficiency compared to the Pangasius system. This is explained by the difference in exergy contained in the co-/by-products of both systems, which surpasses the difference of the total CEENE between them. Finally, the process chains have similar renewability factors, 88.1% for the dairy and 87.1% for the Pangasius, which is a positive aspect of both.

In this study, the exergy-based framework developed offers a comprehensive tool for evaluating resource efficiency in protein production systems, including, in this case, dairy and fish production. By integrating circularity and renewability factors into the CEENE method, this framework provides a more holistic view of resource use and environmental impact. The results highlight key differences in efficiency between land-based and aquatic protein systems, emphasizing the importance of accounting for both renewable and non-renewable resource inputs, as well as the nature of the inputs; whether they are dedicated or non-dedicated. In a global context, where the demand for sustainable food production is rising and the protein transition is gaining momentum, this framework can play a crucial role in guiding resource-efficient practices and policies. It not only helps address the environmental impacts of current production methods but also supports the development of more sustainable food systems worldwide, making it relevant to the global effort to reduce resource consumption and mitigate climate change.

The analysis at the process level has given insight into how these units can be optimized on their own, from a thermodynamic and material perspective. On the other hand, a process chain analysis has given an overview of the overall resource use efficiency of the protein production processes presented in this work. It has been found that agriculturally based protein production systems have prominent levels of renewability, though room for optimization still exists. The renewability factor calculated does not directly distinguish between renewable resources, for example, water obtained from non-renewable water resources and therefore, should be further examined. With appropriate access to data, this framework serves as a starting point to dig deep into resource use efficiency, and allows the user to choose indicators to assess, as it was shown in this example, through mass and exergy analyses. As the food industry continues to evolve, such frameworks will be crucial for guiding sustainable practices and supporting the transition to more efficient and environmentally friendly protein production systems.

Ethical statement

No studies were conducted in humans nor animals.

CRediT authorship contribution statement

Maria Ignacia Rodriguez Escobar: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Erasmo Cadena:** Validation, Supervision, Formal analysis, Data curation. **Trang T. Nhu:** Methodology, Investigation, Data curation. **Sophie Huysveld:** Resources, Methodology, Investigation. **Stefaan De Smet:** Validation, Supervision. **Jo Dewulf:** Validation, Supervision, Conceptualization.

Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2024.100496.

Data availability

Data will be made available on request.

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