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CRITICAL REVIEW

# From food loss and waste to feed: a systematic review of life cycle perspectives in livestock systems

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## Abstract

**Purpose** Food loss and waste (FLW) has become an increasingly important sustainability concern over the past few years. Among the existing waste management strategies, the reintroduction in animal feeding is regarded as a highly advantageous, although the actual benefits should be properly evaluated. The life cycle thinking framework (LCT) enables comprehensive analysis of environmental, economic and social performance. This study explores the main approaches for evaluating the introduction of FLW as feed through the LCT methods.

**Methodology** Using the PRISMA methodology, we conducted a comprehensive review of the existing literature on the topic. To establish a robust research framework, the PICO method was employed to formulate the research questions. The literature search was performed in the Scopus and Web of Science databases, where we identified studies relevant to our topic. After applying rigorous inclusion and exclusion criteria during the screening process, we selected studies suitable for in-depth analysis. The primary goals of this literature review were to assess the bibliographic evolution of the topic and to examine the methodological approaches related to the LCT framework.

**Results and discussion** Our review identified 68 relevant studies that present an increasing trend over the years, denoting a growing interest in the topic. The geographic distribution of the published articles is centred in Europe. It also highlighted the key methodological approaches and their diversity for assessing complex agricultural systems. Regarding the establishment of system boundaries, most of the literature followed a hybrid approach, accounting for environmental rewards but without expanding the analysis to explore further consequences. There was a notable imbalance in the literature distribution among the three methods, with environmental studies being predominant over economic and social analyses. Additionally, many studies employed an integrative approach, incorporating methods to analyze other sustainability aspects.

**Conclusions** Our review of LCT studies of FLW management strategies of feed integration revealed an increase interest in the topic. We investigated key methodological aspects of LCT method in this area. However, limitations remain regarding the research of economic and social aspects, which are less explored in the literature. Addressing these gaps with an integrative perspective would advance knowledge and contribute to develop more resilient and sustainable food systems.

**Keywords** Circular economy · LCA · LCC · S-LCA · Animal nutrition · Agro-industrial residues · By-product valorisation

## 1 Introduction

The generation and disposal of food loss and waste (FLW) constitutes a serious challenge to achieve the sustainability of food systems. It is estimated that in 2020, 13.3% of food was globally lost between harvesting and retail, and an additional 17% was wasted at the consumer stage (United Nations 2022). This is particularly concerning due to the environmental impact associated with food production. According to the IPCC, FLW contributed between 8 and 10% to global GHG emissions for the 2010–2016 period (IPCC 2019). Nonetheless, FLW not only poses an environmental

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burden, but also can aggravate economic and social issues that emerge along the food production chain (De Boni et al. 2022; Vilariño et al. 2017). In terms of economic sustainability, FLW is responsible for economic losses (Abbas et al. 2023; Karwowskaet al. 2021; Vilariño et al. 2017). In Europe, for instance, the annual output of 58.8 Mt of FLW is estimated to have an associated cost of 32€ billion (Commission of the European Communities 2023a, b). Moreover, FLW can further exacerbate social issues such as food insecurity, a significant concern due to the prevalence of world hunger (Santeramo 2021; FAO et al. 2023). Considering these challenges, governments and organizations have implemented various initiatives aimed at reducing FLW.

To address FLW, approaches are being implemented at different scales, including regional initiatives and global cooperative efforts. At the national level, many countries have developed various policy frameworks to address FLW. South Korea serves as an example of successful food waste reduction through measures that include waste prevention, sorting and processing (Lee et al. 2024). On a global scale, the UN Sustainable Development Goals (SDGs) established Target 12.3, aiming to halve per capita global food waste by 2030 at the retail and consumer levels and to reduce food loses in the production and supply chain (United Nations 2015). Moreover, within the Zero Hunger goal, the Target 2.4 seeks to improve sustainability in food production and includes waste management strategies. In 1975, the European Union adopted the *Waste Framework Directive* which included food waste and has undergone multiple revisions to date (Directive 2008/98/EC, 2008). Current efforts under this directive are geared towards setting specific objectives to ensure sufficient action to reach the SDG target in line with the waste hierarchy (Commission of the European Communities 2023b; Papargyropoulou et al. 2014). The waste hierarchy models have been developed by various institutions and establish a prioritised order for food waste management strategies (Sanchez Lopez et al. 2020; US EPA 2023; WRAP 2023). The most preferred waste management strategies are at the top of the hierarchy, while those to be avoided are at the bottom.

One of the strategies to reduce the impact of FLW is its introduction into livestock diets. According to the food waste hierarchy, it constitutes one of the most favourable strategies after redistribution/donations and waste prevention. The use of food residues as livestock feed has long been studied (Owen & Jayasuriyat 1989; Westendorf 2000). However, obstacles to the implementation of this strategy exist, as the use of FLW in animal nutrition is subject to strict regulations in regions such as the EU and the USA, due to past disease outbreaks (Shurson et al. 2023). Besides, novel strategies involving the use of food waste-reared insects for animal feeding are being developed, but their implementation is currently prohibited in the EU (Rasines et al. 2023; Regulation 1069/2009; van Hal et al. 2019). On the other hand, countries like Korea and Japan are further advancing the use of FLW in livestock diets by implementing measures and developing technological advances to ensure safety across the production chain (Nakaishi & Takayabu 2022).

Despite these barriers, integrating food by-products into feed shows advantages in various sustainability aspects. For instance, the reintroduction of food waste as feed has the potential to help alleviate feed-food competition strains (Pinotti et al. 2021; van Hal et al. 2019). Furthermore, it is associated with better environmental performance and a lower cost compared with other feed ingredients (Brehmer & Sanders 2009). This is especially important since feed production is a major contributor to the environmental impact of livestock systems (Agudelo Higuita et al. 2023; Cottee et al. 2022; Gerber et al. 2013). Given the significant role feed production plays in the sustainability of livestock systems, it is crucial to employ accurate methods for measuring its impacts. The life cycle thinking framework (LCT) comprises a holistic approach to assess quantitively the three dimensions of sustainability of products and systems (Mazzi 2020). Altogether, life cycle assessment, life cycle costing and social-life cycle assessment comprise the LCT methodologies to assess the environmental, economic and social sustainability (Toniolo et al. 2020). By considering the stages throughout the life cycle, these methods provide a thorough view of the analysed subjects.

To assess these critical issues, this study aims to analyse the body of scientific literature related to the use of FLW reintroduced as livestock diets and assessed through the life cycle thinking methodologies. To this end, we performed a systematic review to synthesise the existing knowledge on the introduction of FLW into livestock diets, focusing on the environmental, economic and social impacts, with the goal of identifying the main methodological aspects that define the existing scientific research. By collecting and evaluating these studies, we aim to provide useful insights that can inform policy makers, guide future research and support the implementation of sustainable FLW management strategies within the livestock sector.

## 2 Methodology

### 2.1 Systematic review

A systematic literature review was conducted following the PRISMA Statement protocol to avoid bias and increase scientific rigour (Liberati et al. 2009; Page et al. 2021). The focus of this research is to identify studies that use LCT methodologies, for the analysis of FW introduced as feed for animals. There are review studies related to sustainability of food waste valorisation strategies (De Menna et al.

2018; Dominguez Aldama et al. 2023; Omolayo et al. 2021; Redlingshöfer et al. 2020; Santagata et al. 2021). Nonetheless, there is a gap in studies focused on the analysis of the three LCT methodologies for assessing the impacts of food waste used as input for animal feeding, using a systematic review approach. In this light, we propose a systematic review study for circular economy strategies of FLW introduced in livestock feeding assessed using the LCT methodologies.

### 2.2 LCT framework

The LCT framework consists of a systematic methodology for analysing the three pillars of sustainability of a product or system: environmental, economic and social. This framework allows for the analysis of products or systems from a life cycle perspective, from their conception to their disposal. The three domains of sustainability are investigated using different methodological approaches within the LCT framework to tackle the specific aspects of each:

- Life cycle assessment (LCA): is one of the most robust and extended methodologies for quantifying the environmental impacts of a product or system. The LCA methodology is framed under a set of standards that provide robustness and credibility to the analysis (International Organization for Standardization, 2006a; ISO, 2006b).
- Life cycle costing (LCC): it allows to analyse the economic impacts of a product or system. Unlike LCA, there is no general corresponding standard that provides the framework for conducting the analysis. Nonetheless, the methodology has been established in various guidelines (Hunkeler et al. 2008; Swarr et al. 2011).
- Social life cycle assessment (S-LCA): is the least developed and most novel methodology out of the three. Like the LCC, the S-LCA methodology is not framed under an established standard, but the *UN environmental programme* along the *Society of Environmental Toxicology and Chemistry* developed guidelines for conducting this analysis (Benoît & Mazijn 2009; Benoît Norris et al. 2020).

When applying LCT methodologies to evaluate the incorporation of waste as animal feed, a specific concern emerges as it is treated as an end-of-life scenario. By changing the perception of waste as a mere burden and instead considering its potential as a resource with continuous use, the introduction of FLW as animal feed differs from conventional waste management studies (Moraga et al. 2018). The means of approaching these kind of scenarios initiates discussion among scholars about methodological aspects regarding the inclusion of environmental benefits and the extension of system boundaries (Ekvall et al. 2016; Schaubroeck et al. 2021; Schrijvers et al. 2016). In this context, there are two differentiated approaches, depending on whether the analysis should include the accounting for additional credits through system expansion or not. Attributional LCA accounts for impacts directly to studied activities or processes, overlooking broader considerations linked to the valorisation of waste. On the other hand, consequential LCA involves a process of system expansion, aiming to evaluate the systemic changes after a shift in the existing system (Earles & Halog 2011; Sonnemann & Vigon 2011). Hence, the selection of one approach over the other is of significant consequence as they entail different procedures that lead to divergent outcomes (Fauzi et al. 2021; Rehl et al. 2012).

Some institutions are actively advancing the implementation of the LCT framework as a tool for research and decision-making (Sala et al. 2021). For instance, the EU has initiatives such as the European Platform on LCA and directives like the Ecodesign directive, which promote the use of this methodology in organisations and industries (Directive 2009/125/EC 2009). It is also notable that there is increasing interest in the application of the methodology for assessing waste management strategies, including FLW (De Laurentiis et al. 2020, 2024; Omolayo et al. 2021). In view of the popularity of the LCT methods and the expanding topic of FLW circularity, we believe it is relevant to explore and discuss the main methodological aspects currently employed. By systematically reviewing the existing body of knowledge on FLW introduced as livestock feed, we aim to uncover the key LCT factors that characterise these kinds of studies.

### 2.3 Research questions

The PICO methodology (Aslam & Emmanuel 2010) was followed to formulate the main research questions based on the objectives of this literature review. This methodology enables us to define the keywords that encapsulate the ideas we aim to examine. The establishment of these terms also helps later on with the literature collection stage. Figure 1 depicts the PICO scheme based on the problem, intervention, comparison and outcome indicators. In the problem element, we included two components, one referred to food and the other to waste. The comparison terms were used as a reference, as the goal of this research was not to draw a parallel between livestock feeding and other circular economy strategies. Following the establishment of keywords, the research questions were formulated to align with the topic and to effectively focus on the study's objectives:

- Q1: What is the contribution of FLW management introduced as livestock feed studies to the academic literature from the LCT approach?

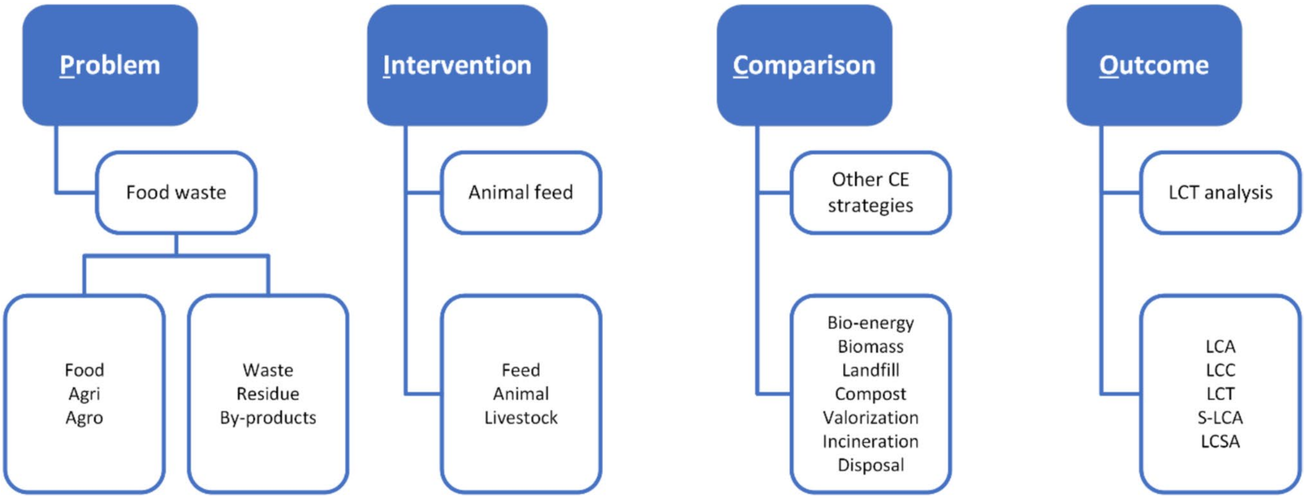


**Fig. 1** PICO method scheme adapted from the LEEDS University PICO concept map (completed PICO concept map | Library | University of Leeds, n.d.)

- Q2: What are the methodological approaches for circular treatment of FLW used as feed analysed with the LCT methods?
- Q3: What is the share of contribution of each LCT methodology approach to the existing body of knowledge?
- Q4: What are the main LCA, LCC and S-LCA parameters used across the studies?

## 2.4 Document collection

The collection of documents included all studies up until the year 2024. The search was carried out in the academic databases Scopus and Web of Science. The search key for Scopus was selected as a title, abstract and keywords search with the following string: TITLE-ABS-KEY (((agro* OR agri* OR food) AND (waste* OR residue* OR by-product*)) AND (feed AND (livestock OR animal)) AND ((life AND cycle AND assessment) OR lca OR (life AND cycle AND costing) OR lcc OR lifecycle OR *lca) AND NOT (municipal AND waste) AND NOT (household)). 'Municipal waste' and 'household' were introduced as excluding terms after some search trials, given that they refer to FLW mixed with other non-organic residues, thereby achieving a more accurate collection of records after their omission. After the initial collection of literature, the final selection of studies was performed according to the PRISMA framework, which is described in the following section.

## 2.5 Selection and evaluation

To ensure the rigour and focus necessary to conduct a systematic review, it is important to define the topic and set precise boundaries (Bruzzese et al. 2023). Through the establishing of inclusion and exclusion criteria, we can filter and narrow down the academic literature relevant to the purpose of this study (Page et al. 2021). Furthermore, it enables us to explore and select the studies that meet eligibility criteria, avoiding excessive complexity. Considering all factors, the inclusion criteria set comprise the following points:

- Academic (white) literature written in English and published in peer-review journals.
- Studies that contribute to the body of knowledge of FLW used as animal feed by means of LCT methodologies, including studies that evaluate other waste management strategies for comparison.
- Case studies examining specific types of FLWs and their valorisation pathways, whether focusing on a particular example or adopting a broader perspective.
- Documents written in the form of academic articles and conference proceedings.

Conversely, the exclusion criteria are delineated as follows:

- Articles that only address circular economy strategies for FLW other than its introduction in livestock feed.
- Case studies of by-products from energy crops originally intended for energy purposes only.
- Review articles that do not involve performing case study analysis.

After the establishment of exclusion and inclusion criteria, our review study followed the screening process outlined in the PRISMA protocol, which is depicted in Fig. 2. The articles obtained from the databases search were subjected

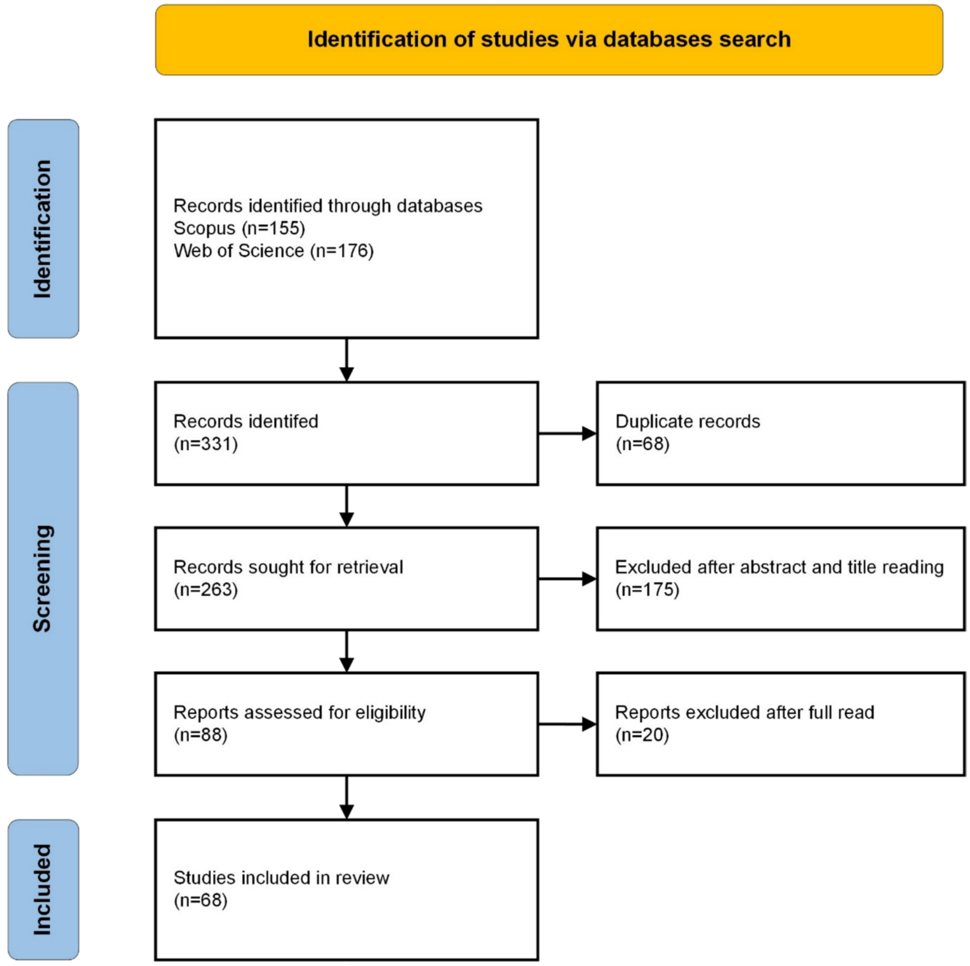


**Fig. 2** Identification and screening of records workflow based on the 2020 updated PRISMA flow diagram (Page et al. 2020)

to a thorough evaluation against the predetermined criteria, ensuring their alignment with the study's objectives and parameters. Firstly, the documents obtained were filtered to avoid duplicates. Then, an initial screening was performed through the reading of titles and abstracts. Lastly, a full reading of the remaining articles was carried out to obtain the final documents to be included in the analysis. In total, 68 documents were eligible for inclusion and later analysis. This approach not only enhances the credibility and robustness of our systematic review, but also facilitates the extraction of meaningful insights and conclusions while setting parameters that are relevant to the topic and methodology investigated.

## 3 Results and discussion

### 3.1 Bibliographical aspects

This section focuses on analysing the main publication details from the selected studies, such as the chronology of publication. The distribution of publications by year is depicted in Fig. 1 of the Supplementary Material. This distribution shows an increasing trend, starting from the two first studies issued in 2007. The years with the highest number of published articles are 2021 and 2023, with 9 and 10 articles each. Regarding the geographical distribution of the case studies, most research is focused in Europe, with 39 articles. The documents collected include 16 case studies from the American continent and 13 from Asia. The continents with the fewest case studies are Oceania, with 3 articles, and Africa, which has none. Two articles analyse multiple case studies in different countries or regions (Brehmer & Sanders 2008; Renouf et al. 2008), resulting in the total number of cases exceeding the number of documents collected. The country with the highest number of reference scenarios is Spain, followed by UK and Brazil, with 8, 6 and 5 articles each. Additionally, 7 articles use Europe as a case study, in a broader perspective.

Regarding the scientific journals in which the studies are published, most of the retrieved literature is published in the Journal of Cleaner production with 13 articles. Then, Science of the Total Environment and Sustainable Production and Consumption are the second and third most frequent journals, with 10 and 5 studies each. Generally, these journals are among the most popular academic journals for LCT studies.

The majority of research is focused on FLW generated in the production stage, with 45 records centred around this topic. This aligns with the statement of Albizzati et al. (2021), "…most published studies addressing the subject focus on pre-consumer food waste…" (p. 16099). Studies on FLW management obtained from multiple sources, retail and consumer levels account for 11, 6 and 4 studies, respectively. Even though this review focused on the implementation of FLW in livestock feeding, many studies also explore alternative strategies through comparative scenarios. Following the use as animal feed, the most analysed strategy is the energy valorisation, with 36 articles. Then, 22 studies considered comparing animal feeding with disposal scenarios, either landfilling or incineration without energy recovery. Other scenarios include composting (22 studies), compound recovery for non-food applications (10 studies), reprocessing into human food (5 studies), donations (5 studies) and waste prevention (3 studies).

### 3.2 General life cycle thinking attributes

Table 1 summarizes a selection of LCT arguments that describe the methodological aspects of the articles collected. In terms of the sustainability dimensions addressed, all items perform an environmental analysis, while the economic and social life cycle methodologies are significantly less represented, appearing in only 6 and 3 studies each. Regarding the methodological approach, 34 studies employ a hybrid method. This approach does not consider systemic changes like the conventional attributional method but does account for avoided impacts or burdens, similar to the consequential method. This often results in more favourable outcomes. The classic attributional approach is used in 22 studies, while 12 utilise the consequential approach. The consequential perspective requires formulating more assumptions due to the lack of available data for the hypothetical scenarios, which may influence researchers, making them hesitant to employ it. On the other hand, 43 studies are found to use an input–output approach, while 24 perform process-based analysis. One study mentions the use of a hybrid approach and another one employs a process-based perspective but performs a scale-up at industry level. Input–output usually entails the use of secondary data for modelling a market overview; nonetheless, the majority of documents reports the use of primary data. Out of the 54 studies that report using primary data, all also incorporate secondary sources, often obtained from databases for background processes related to environmental data. Additionally, 13 studies rely exclusively on secondary data, while 1 study neither reports nor provides information on the origin of its data. Methodological differences across continents are challenging to assess due to the uneven distribution of studies. Regarding sustainability dimensions, Asia and Europe have conducted LCC studies, with Europe also exploring S-LCA, whereas other regions focus solely on the environmental dimension. Concerning the applied approaches, Europe and America tend to favour a hybrid approach, while Asia predominantly employs the attributional approach, and Oceania exclusively applies the attributional method. In terms of study types, America demonstrates an equal distribution between input–output and process-based approaches, while other regions primarily rely on input–output data-based studies.

Multifunctionality is a major issue to deal with in LCT studies in which by-products are the focus. Depending on the type of approach, the use of allocation methods is frequent in these kinds of studies. About half of the documents do not report the use, or do not specify the type of allocation employed in their research. The remaining studies either use economic, mass or energy allocation, with 20, 12 and 6 studies, respectively. Moreover, some articles perform more than one type of allocation, often to tackle the uncertainties of the data. Frequently, in LCT research, sensitivity or uncertainty analyses are carried out to address data uncertainty. In the literature covered, we found that 44 studies use these methods, of which eight studies report the use of a Monte Carlo model analysis. The Monte Carlo model is popular in life cycle studies due to its implementation in LCA software (Heijungs 2020).

A noteworthy aspect of the retrieved literature is that there are two ways in which the topic of food waste is addressed; in 39 records, FLW is not the focus of the study, but is managed as a secondary aspect; otherwise, in 26 articles, FLW is the centre of the research, entailing waste-focused research. The remaining three records tackle both in the articles. This influences the way the systems boundaries are set, as most of the waste-focused studies do not include the agricultural or production stages (bin-to-grave), while product-centred articles often set the boundaries as a cradle-to-gate approach. The functional unit is another factor that is directly affected by the subject focus, although in both product and waste articles, the main functional unit employed is based on mass. Out of the 68 records, 61 use a mass unit: 32 articles use tons, 29 use kilograms and one uses both. Although some records use alternative functional units, like volume or energy, in any case, the most commonly used value is one unit of product or waste, as reported in 56 studies.

Figure 3 showcases a Sankey diagram illustrating three interconnected aspects in LCT studies, concerning FLW used as animal feed: the type of waste assessed, the type of displacement used in product substitution and the products avoided from the livestock feed. The main type of singular waste analysed is fruits and vegetables, with 10 studies, followed by grains with 9 studies. Moreover, 5 studies

**Table 1** Selection of main methodological life cycle thinking parameters extracted from the collected articles

| ID | LCT dimension | | | Approach | Data | Allocation | | | | Continent |
|---|---|---|---|---|---|---|---|---|---|---|
| | LCA | LCC | S-LCA | | | Economic | Mass | Energy | N/A | |
| [1] | ✓ | | | Hybrid | Hybrid | ✓ | | | | Eu |
| [2] | ✓ | | | Hybrid | Input–output | | | | ✓ | Eu |
| [3] | ✓ | | | Hybrid | Input–output | | | | ✓ | CCo |
| [4] | ✓ | | | Attributional | Input–output | | ✓ | | | Eu |
| [5] | ✓ | ✓ | | Consequential | Input–output | | ✓ | | | As |
| [6] | ✓ | | | Attributional | Input–output | | | | ✓ | As |
| [7] | ✓ | | | Hybrid | Input–output | | | | ✓ | Eu |
| [8] | ✓ | ✓ | | Hybrid | Input–output | | | | ✓ | As |
| [9] | ✓ | | | Hybrid | Process-based | ✓ | | | | Am |
| [10] | ✓ | | | Hybrid | Input–output | | | | ✓ | Eu |
| [11] | ✓ | | | Hybrid | Input–output | | | | ✓ | Eu |
| [12] | ✓ | | | Attributional | Input–output | | | | ✓ | Eu |
| [13] | ✓ | | | Hybrid | Input–output | | ✓ | ✓ | | Eu |
| [14] | ✓ | | | Hybrid | Input–output | | | | ✓ | Am |
| [15] | ✓ | | | Attributional | Input–output | ✓ | ✓ | | | As |
| [16] | ✓ | | | Consequential | Input–output | | | | ✓ | Eu |
| [17] | ✓ | | | Hybrid | Process-based | | | | ✓ | As |
| [18] | ✓ | | | Hybrid | Process-based | | | | ✓ | Eu |
| [19] | ✓ | | | Consequential | Input–output | ✓ | | | | Eu |
| [20] | ✓ | ✓ | | Consequential | Input–output | | | | ✓ | Eu |
| [21] | ✓ | | | Attributional | Input–output | ✓ | | | | Oc |
| [22] | ✓ | | | Attributional | Process-based | ✓ | ✓ | ✓ | | Oc |
| [23] | ✓ | | | Attributional | Input–output | | | | ✓ | As |
| [24] | ✓ | ✓ | ✓ | Consequential | Input–output | | | | ✓ | Eu |
| [25] | ✓ | | | Consequential | Input–output | | | | ✓ | As |
| [26] | ✓ | | | Hybrid | Input–output | ✓ | | | | Eu |
| [27] | ✓ | | | Attributional | Input–output | ✓ | | | | As |
| [28] | ✓ | | | Attributional | Input–output | ✓ | | | | Eu |
| [29] | ✓ | | ✓ | Attributional | Process-based | | | | ✓ | Eu |
| [30] | ✓ | | | Consequential | Process-based | | | | ✓ | Eu |
| [31] | ✓ | | | Hybrid | Input–output | ✓ | | | | As |
| [32] | ✓ | | | Hybrid | Input–output | | | | | CCo |
| [33] | ✓ | | | Attributional | Input–output | ✓ | | | | Eu |
| [34] | ✓ | | | Hybrid | Process-based | ✓ | | | | Am |
| [35] | ✓ | ✓ | | Hybrid | Hybrid | | | | ✓ | Eu |
| [36] | ✓ | | | Hybrid | Process-based | | | | ✓ | Eu |
| [37] | ✓ | | | Consequential | Input–output | | ✓ | | | Am |
| [38] | ✓ | | | Hybrid | Input–output | | | | ✓ | Am |
| [39] | ✓ | | | Hybrid | Input–output | ✓ | ✓ | | | As |
| [40] | ✓ | | | Hybrid | Input–output | | | | ✓ | Eu |
| [41] | ✓ | ✓ | ✓ | Attributional | Input–output | ✓ | | | | Eu |
| [42] | ✓ | | | Consequential | Process-based | | | ✓ | | Am |
| [43] | ✓ | | | Hybrid | Process-based | | | | ✓ | Eu |
| [44] | ✓ | | | Hybrid | Process-based | | | | ✓ | Eu |
| [45] | ✓ | | | Hybrid | Input–output | ✓ | | | | Eu |
| [46] | ✓ | | | Attributional | Input–output | | | ✓ | | Am |
| [47] | ✓ | | | Hybrid | Process-based | | | | ✓ | Eu |
| [48] | ✓ | | | Hybrid | Input–output | ✓ | | ✓ | | Eu |
| [49] | ✓ | | | Hybrid | Input–output | | | | ✓ | Am |

**Table 1** (continued)

| ID | LCT dimension | | | Approach | Data | Allocation | | | | Continent |
|---|---|---|---|---|---|---|---|---|---|---|
| | LCA | LCC | S-LCA | | | Economic | Mass | Energy | N/A | |
| [50] | ✓ | | | Attributional | Process-based | ✓ | | | | CCo |
| [51] | ✓ | | | Consequential | Input–output | | | | ✓ | Eu |
| [52] | ✓ | | | Hybrid | Process-based | | | | ✓ | Am |
| [53] | ✓ | | | Attributional | Process-based | ✓ | | | | Eu |
| [54] | ✓ | | | Hybrid | Input–output | | | | ✓ | Am |
| [55] | ✓ | | | Hybrid | Input–output | ✓ | | | | Eu |
| [56] | ✓ | | | Attributional | Process-based | | | | ✓ | Eu |
| [57] | ✓ | | | Attributional | Input–output | | ✓ | | | Am |
| [58] | ✓ | | | Attributional | Process-based | | | | ✓ | Am |
| [59] | ✓ | | | Hybrid | Process-based | | ✓ | | | Eu |
| [60] | ✓ | | | Hybrid | Process-based | | | ✓ | | Am |
| [61] | ✓ | | | Hybrid | Process-based | | | | | Eu |
| [62] | ✓ | | | Hybrid | Input–output | | | | ✓ | Eu |
| [63] | ✓ | | | Hybrid | Input–output | | | | ✓ | Eu |
| [64] | ✓ | | | Consequential | Input–output | | | | ✓ | As |
| [65] | ✓ | | | Attributional | Input–output | | ✓ | | | Eu |
| [66] | ✓ | | | Attributional | Process-based | | ✓ | | | As |
| [67] | ✓ | | | Attributional | Process-based | | | | ✓ | Eu |
| [68] | ✓ | | | Attributional | Process-based | ✓ | ✓ | | | Am |
| Total | 68 | 6 | 3 | | | 20 | 12 | 6 | 35 | |

The names of the continents have been abbreviated as follows: Am: America; As: Asia; CCo: Cross-continent; Eu: Europe; Oc: Oceania

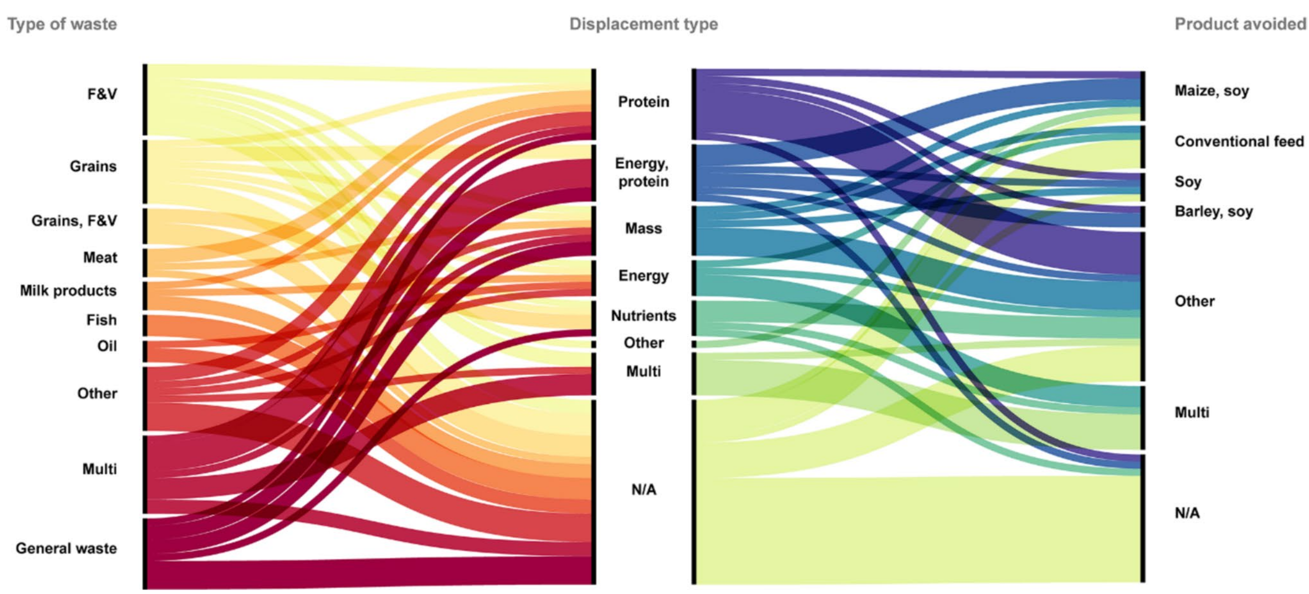


**Fig. 3** Sankey diagram of the type of waste analysed, the type of displacement used and the avoided products from the introduction of food waste as feed in livestock diets in the literature. Categories labelled as 'Multi' encompass the use of multiple items in the same study. The 'Other' categories include single items which appeared in less than three studies

examine both fruits and vegetables and grains, constituting a third of the articles collected exploring these waste types. On the other hand, a mix of various food groups is analysed in 11 other studies, while 10 studies focus on general FLW. The type of displacement refers to the criteria used to quantify the amount of avoided product during the substitution process. The most common substitution methods are based on protein quantity (10 studies), a combination of energy and protein indicators (8 studies), and mass (7 studies), which refers to displacement based on the equivalence of matter quantity. In 26 studies, the displacement type is not specified, either because product substitution is not performed, or the type of displacement is not declared. Regarding avoided feed products, the literature shows a diverse range of substituted products, with the 'other' category comprising 21 articles. The most common replaced products are a mix of maize and soy and conventional feed, with 7 and 6 records, respectively. Similar to the type of displacement, a significant number of articles, 18 in total, do not account for avoided products or fail to mention them. Overall, the Sankey diagram displays a high degree of methodological heterogeneity regarding displacement implementation, as the same FLW categories flow into different displacement types and subsequently avoided products. This variability may stem from a lack of a harmonised methodology in implementing displacement in LCT studies.

### 3.3 Life cycle assessment

Figure 4 illustrates the impact categories by type of waste used in LCA studies, providing an overview of the importance of environmental indicators for food waste used as feed. There are no major differences between the food categories studied and environmental indicators assessed. Milk products, along with other and general waste, exhibit a more evenly distributed range of impact categories, while the remaining waste types focus on a narrower set of impact categories. The most commonly analysed impact category across literature is Global Warming Potential, featured in 65 studies, reflecting its prominence due to climate change concerns. Following this, categories such as Eutrophication Potential and Acidification Potential appear in 37 and 33 studies, respectively. Only 10 studies employ Endpoint or damage indicators, with six using the ReCiPe Endpoint method, three using Impact 2002 + and one using the Environmental Footprint method. The most frequently used life cycle impact assessment method overall is ReCiPe method, applied in 21 studies, followed by IPCC and CML, found in 12 and 11 documents, respectively.

The main LCA software of choice among the studies is Simapro, which is used in 28 studies. On the other hand, 23 records either do not declare or do not make use of LCA software for the analysis. In the remaining 19 studies, the software employed is more varied, including tools such as Gabi, Open LCA and EASETECH. Regarding the use of environmental databases, the most prevalent is Ecoinvent, being mentioned by 42 studies. Besides, 22 studies don't declare the use of any specific LCA database. Nonetheless, other databases are used for environmental data, like governmental and organisational databases like FAOSTAT.

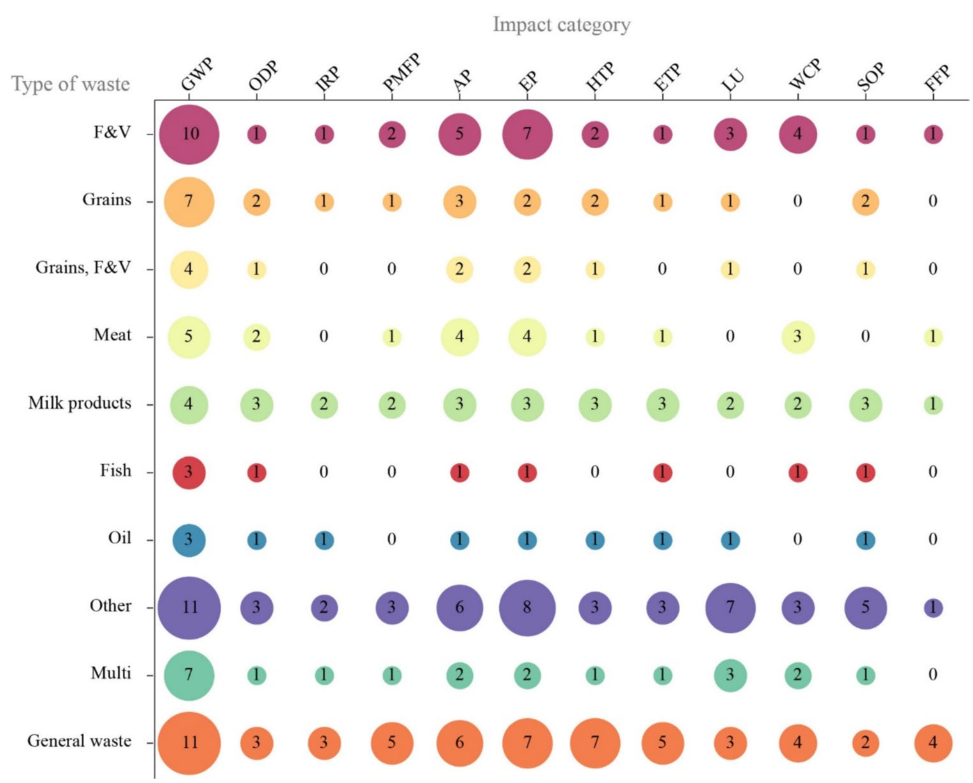


**Fig. 4** Frequency of environmental impact categories in the retrieved literature based on the type of waste analysed. Note: To harmonise the Midpoint impact categories, they were synthesised and labelled based on an adaptation of the ReCiPe 2016 framework (Huijbregts et al. 2017). GWP, global warming potential; ODP, ozone depletion potential; IRP, ionising radiation potential; PMFP, fine particulate matter formation potential; AP, acidification potential; EP, eutrophication potential; HTP, human toxicity potential; ETP, eco-toxicity potential; LU, land use; WCP, water consumption potential; SOP, surplus mineral and metal ore depletion potential; FFP, fossil fuel depletion potential

### 3.4 Life cycle costing

As previously mentioned, only 6 studies within the 68 included in this research conduct LCC analysis. However, the implementation of other economic analysis methodologies is present in the selected documents, such as techno-economic assessment and cost–benefit analysis, which amount to 4 and 2 records each. Since these studies also perform LCA, it can be considered that the economic analyses have been conducted from a life cycle standpoint. Therefore, a total of 12 records carry out some sort of economic analysis and have been included in this section for discussion. Table 2 summarises the LCC studies and their main parameters.

Akin to LCA, LCC can be categorised depending on the scope of the economic analysis, accounting for further economic implications through externalities. Thus, three kinds of LCC are referred to as conventional (C-LCC), environmental (E-LCC) and social (S-LCC) (De Menna et al. 2016). Out of the 6 studies which use the LCC approach, 3 declare the LCC approach selected (Albizzati et al. 2020, 2021; Kim et al. 2011). The remaining records have been classified by the methodological criteria set by the LCC guidelines (De Menna et al. 2016). The most common approach is the C-LCC, with 11 documents having made use of it. In the remaining 2 studies, one record employed the E-LCC and one the S-LCC approaches. The preference for using C-LCC over E-LCC and S-LCC might be due to a lower availability of data and higher uncertainty for environmental and social economic parameters.

The studied literature presents a wide diversity of economic indicators, although not all articles transparently describe the means of calculating the parameters. Six studies address initial investment costs through indicators like capital expenditure. Variable costs are included in all studies through a diverse range of indicators, such as maintenance costs, operational costs and raw materials. Three studies use the net present value (NPV) as an economic indicator; additionally, 2 of them include the internal rate of return (IRR), and one the payback period time (PBT). These three indicators serve as a measure for guiding investment decisions and are often included together in studies for comparison, specially the NPV and IRR (Chen et al. 2020; Escamilla-García et al. 2020; Larrain et al. 2021). The article which performs an E-LCC uses carbon credits as an environmental economic indicator. On the other hand, the study that employs an S-LCC approach, calculates shadow prices to address externalities.

### 3.5 Social life cycle assessment

Although the relevance of the social sustainability aspects of the present topic is remarkable, only 3 studies have been identified in the screening that analyse this through the life cycle approach. This aligns with the distribution of published literature for S-LCA compared to other life cycle methodologies in studies of other topics, which typically contribute less to the general body of knowledge of the LCT studies. Iofrida et al. (2018) argue that the lack of a robust social sustainability theoretical base poses a challenge for academics to engage in S-LCA research. The main aspects

**Table 2** Life cycle costing and economic analysis by type and economic indicators reported

| Economic analysis | ID | LCC type | Economic indicators |
|---|---|---|---|
| LCC | [5] | C-LCC, E-LCC | Cost–benefit analysis (discharge, collection, storage, transportation, treatment/disposal costs), market prices of by-products, carbon prices |
| | [8] | C-LCC | Running costs (maintenance, labour, and utility cost) and revenue |
| | [20] | C-LCC, S-LCC | Factor prices (budget costs), shadow prices (factor prices multiplied by net tax factor) |
| | [24] | C-LCC | Capital expenditure, operational expenditure, end-of-life expenditure, revenues, prosperity (endpoint) |
| | [35] | C-LCC | Raw materials costs, capital costs, maintenance costs, transportation costs, distribution costs, storage costs, waste management costs, co-products revenue, annual value added |
| | [41] | C-LCC | Contribution margin, revenues, variable costs |
| Technoeconomic | [9] | C-LCC | Prospective economic performance, maximum-purchasing-price, minimum-selling-price, annual recovery of capital, operation costs, total investment costs |
| | [42] | C-LCC | Net present value, internal rate of return, capital expenditure, revenues, operational costs |
| | [51] | C-LCC | Net present values, internal return rate, payback period time, fixed capital investment, incomes, costs, EBIDTA, amortization, cash flows |
| | [62] | C-LCC | Market value (acquisition cost, depreciation costs, processing costs, logistic costs, 5% net profit) |
| Cost–benefit analysis | [16] | C-LCC | Cost by retailers, gate fee, tax credits |
| | [29] | C-LCC | Raw material cost, capital costs, operational and maintenance costs, sales revenue, utilities cost, and government subsidies/incentives, net present value |

assessed by the articles are presented in Table 3. Regarding the type of S-LCA approach, two kinds of studies are distinguished, reference scale and impact pathway. While reference scale involves assessing social performance, the impact pathway perspective explores further consequences, similar to the consequential approach (Traverso et al. 2021). Although none of the 3 articles specify the type of analysis employed, they adopt the reference scale type of S-LCA.

The limited number of studies precludes identifying patterns in the social indicators employed. All studies incorporate at least one indicator related to labour welfare, such as working hours or job creation. Two studies also assess odour generation, likely due to handling waste, a concern also noted in other studies examined that do not conduct S-LCA (Lee et al. 2007; Ogino et al. 2007). One article proposes using human nutritional indicators (human-consumable calories and protein) to assess feed-food competition. Factors like feed-food competition or food security could be significant indicators in FLW studies, although few studies have addressed them. However, food security and feed-food competition have been considered in other studies reviewed for this research (Bais-Moleman et al. 2019; Misra et al. 2023; van Hal et al. 2019; zu Ermgassen et al. 2016).

### 3.6 Other methodological approaches

As mentioned before, this research aims to assess how LCT methodologies contribute to the body of knowledge regarding FWL implemented as animal feed. However, within the realm of sustainability in complex and multifunctional systems, other methodological approaches are often employed to complement LCT methods, achieving a more holistic perspective. Other methods employed include nutrient circularity, circularity indicators, multicriteria analysis, spatial analysis and SWaVI analysis. These approaches are commonly integrated into sustainability research alongside LCT methods to address trade-offs and enhance clarity of results (Zanghelini et al. 2018). Circularity and nutrient circularity analysis are particularly relevant for studying FLW, while spatial analysis provides insights into project efficiency based on resource allocation and management, aspects beyond the scope of LCT methods alone. Together, these complementary methods offer valuable insights into the nuances of sustainability research on FLW as animal feed.

### 3.7 Food loss and waste to feed emissions mitigation potential

A quantitative analysis was conducted to explore the extent of environmental impact of FLW used as feeding. The analysis primarily focused on the GWP impact category, which was the most frequently reported across the included studies. Due to significant methodological heterogeneity among studies, a standardization of the variable was implemented, estimating the impact per 1 kg of waste. Articles that could not be converted to this unit were discarded. Moreover, studies were required to include the impacts associated with waste-to-feed processing as well as emissions mitigation through the displacement of conventional feeds. Most studies considered FLW to be burden free before processing; therefore, this assumption did not exclude them for the analysis. The estimated emissions were categorized by food group, enabling the calculation of average emissions for each group. The final number of articles for each food group is as follows: general waste: 6; fruits: 3; vegetables: 4; grains: 7; dairy: 2; fish: 2; and meat: 3. Furthermore, the analysis explored the impacts on the European market of FLW used in feed, incorporating data from Caldeira et al. (2019) to estimate the amount of FLW directed towards animal feed by food group.

Figure 5a displays the results for the average GWP values across studies. The food groups with higher emissions mitigation are fish, dairy and meat, with −0.550, −0.416 and −0.401 kg of $CO_2$ eq, respectively. This suggests that animal products offer greater environmental impact reductions per kg of FLW processed. In contrast, fruits, vegetables and grains provide the lowest environmental benefits. This finding is significant because, given livestock dietary restrictions, introducing a smaller amount of FLW might be more feasible, thus amplifying the impact of animal products. Meanwhile, Fig. 5b illustrates the emissions reductions from FLW used in animal feed within Europe. Grains, dairy and fruits are the most commonly integrated into feed, while mixed general waste and meat are largely restricted from inclusion in livestock diets. Consequently, the latter do not

**Table 3** Social life cycle assessment studies by type and declared indicators included in the study

| ID | Type of S-LCA (reference scale, impact pathway) | Social indicators |
|---|---|---|
| [24] | Reference scale | Urban space consumption, odour, landscape disamenities, private space consumption, total employment, occupational health, human well-being (endpoint) |
| [29] | Reference scale | Social acceptability, odour generation, noise creation, job creation, traffic generation |
| [41] | Reference scale | Working time, human-consumable calories and protein |

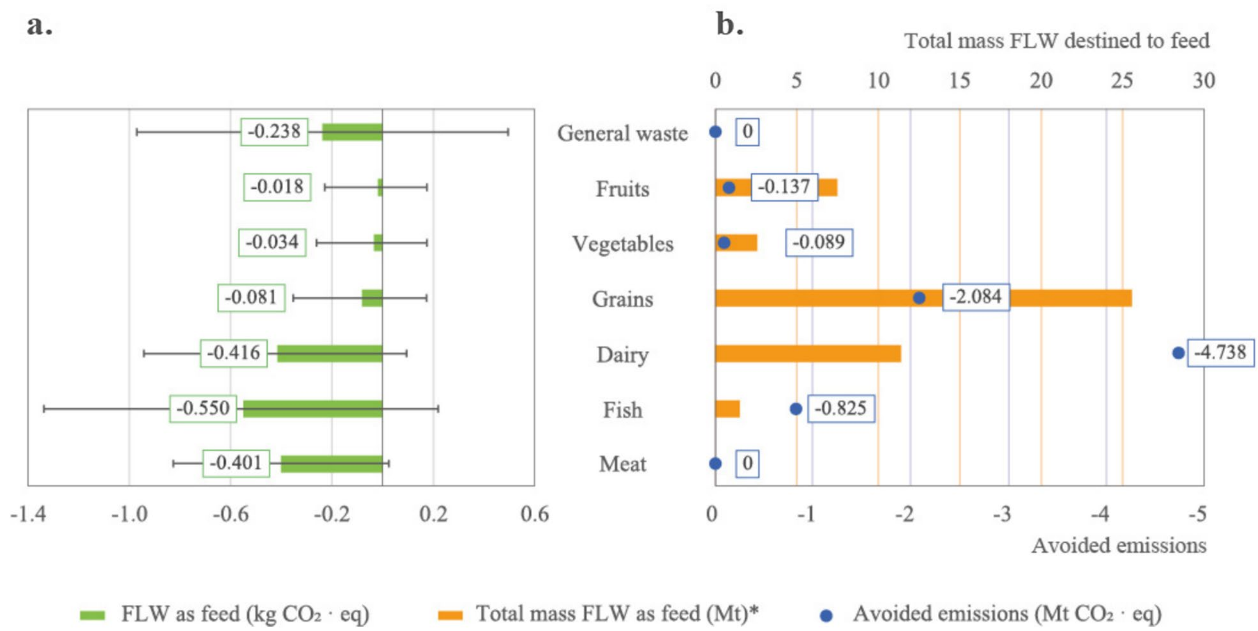


**Fig. 5** **a** Average GWP impact of 1 kg of FLW processed as feed by food group in kg of CO2 eq. Error bars indicate the standard deviation of each estimation. **b** Total FLW mass allocated to animal feed and the calculated greenhouse gas (GHG) emissions avoided for each food group in Europe. *Data retrieved from Caldeira et al. (2019)

contribute to the alleviation of carbon emissions. The primary driver of emissions reduction through FLW as feed is the recycling of dairy products, which accounts for 4.738 Mt of $CO_2$, representing 60% of the total GWP mitigation. Grains contribute 26% to the overall emissions reduction. Although their emissions mitigation per kilogram is lower, their widespread use results in a significant impact on the overall market's emissions reduction. Fish residues amount to 9% of the carbon removals, while fruits and vegetables represent the lowest mitigators, with 2% and 1%, respectively. While the environmental benefits per kilogram of FLW vary by food group, the large-scale implementation of certain food types, such as dairy and grains, can have a substantial cumulative effect on emissions reduction across the market. However, the feasibility and impact of this approach depend on both the types of FLW available and the dietary restrictions of livestock, highlighting the need for strategic planning in FLW recycling to maximize environmental benefits.

## 4 Discussions

This systematic review offers a novel synthesis of the sustainability implications of FLW used as animal feed, with a particular emphasis on the methodological aspects of LCT methods. Unlike previous reviews, this study specifically addresses the recirculation of waste as animal feed, providing a comprehensive analysis of this utilisation pathway and its unique complexities. By addressing the distinct challenges and opportunities associated with this approach, the review distinguishes itself from broader studies on FLW management strategies (Amicarelli et al. 2021; Dominguez Aldama et al. 2023; Redlingshöfer et al. 2020). The study by Shurson (2020) also examines the implementation of FLW as animal feed, addressing a range of issues, including environmental impacts. However, it lacks a methodological assessment, focusing instead on other aspects, such as the nutritional components of waste and its safety for animal consumption. Similarly, De Menna et al. (2018) review the literature on methodological choices in the LCC of food waste, highlighting variability in methodological approaches and economic indicators. However, their classification of LCC types differs from this study's framework. For instance, they consider all LCC studies paired with an LCA as E-LCCs, whereas this review includes environmental externalities as a defining characteristic of E-LCCs, leading to a different number of records for each LCC type. The increasing recognition of FLW as a critical area of study continues to push research forward, despite the challenges and limitations associated with its management, especially in feed applications.

The review reveals a significant geographic imbalance in FLW research, with most studies concentrated in Europe, leaving regions like Africa critically underrepresented. This disparity is particularly concerning given the pressing issue of food insecurity across Africa, where FLW exacerbates challenges in accessing sufficient, safe and nutritious food (Affognon et al. 2015; Vos et al. 2021). Additionally, many countries in Africa are experiencing the largest growth in cropland area, and the region generates a significant portion of the FLW generated globally (Abbade 2023; Berjan et al. 2018). Despite the continent's vulnerability to food loss and waste, there is a lack of localized research applying LCT methodologies to address these issues. Although LCT methodologies are becoming more widespread on the continent, research remains limited and is largely concentrated in economically dominant countries (Karkour et al. 2021). Conducting LCT-based research in Africa could provide valuable insights into how FLW reduction strategies can not only improve sustainability but also contribute to alleviating food insecurity. Expanding the geographic scope of FLW studies would ensure that strategies are more inclusive and globally relevant, addressing the urgent need for equitable food systems worldwide.

This study highlights that the selection of economic indicators strongly depends on the specific objectives of the economic assessment in the context of using FLW as animal feed. Indeed, the reviewed literature shows a considerable variety of economic indicators, and thus, their selection should reflect the aspects that most influence the economic sustainability of FLW usage. Economic indicators related to production and transformation costs are useful for assessing the operational efficiency of the system (Daskalopoulou 2022), and the integrated adoption of LCC analysis allows for a comprehensive assessment, including costs associated with waste management and the end-of-life phase (Knauer and Möslang 2018). Other approaches, based on the use of financial performance indicators, such as return on investment (ROI), NPV, payback period and IRR, are useful for evaluating the profitability of the process of utilizing FLW as feed, helping to determine whether the initial investment is justified by long-term economic returns (Arnaboldi et al. 2015). Therefore, for an optimal evaluation, it would be advisable to combine different economic indicators that consider both direct and indirect aspects, such as the benefits derived from waste reduction and the environmental impacts associated with the use of FLW.

The social dimension of sustainability has been the least addressed pillar in the analysed literature. Usually, S-LCA studies are less abundant in comparison to LCA and LCC because the methodology is less developed and standardized (Larsen et al. 2022). One major challenge lies in the lack of universally agreed-upon indicators for assessing social impacts. Social indicators are inherently linked to economic sectors, and developing an adequate set of indicators involves the identification of the stakeholders across the whole value chain (Lago-Olveira et al. 2024). Within the context of FLW, various interconnected sectors—such as transportation, waste management and agriculture—play critical roles in the supply network. The retrieved literature assessed social indicators like odour and labour related metrics. Luthin et al. (2023) explored social circular economy indicators, which are generally related to end-of life management strategies. Some specific subcategories include public commitments to sustainability issues, end-of-life responsibility and transparency. As previously mentioned, other critical issues related to FLW used as animal feed involve food security and feed-food competition. However, given the data-intensive nature of S-LCA studies, the challenges in obtaining necessary data and the complexity of quantification and interpretation of the indicators, the standardisation of S-LCA categories should be prioritized to promote the broader application of the methodology (Pollok et al. 2021).

The future lines of research regarding FLW applied as livestock feed, through the lens LCT methodologies, should address several critical points to advance the field. First, there is a need for standardization of methods, particularly in the selection of indicators used for assessing environmental, economic and social impacts. Clear and consistent metrics will allow for meaningful comparisons across studies.

The declaration of system boundaries is also a key issue, as defining what constitutes the FLW, how the impact of production should be allocated to the waste through food and agricultural systems are crucial considerations. Similarly, the distinction between attributional and consequential approaches in LCT is pivotal to ensure transparency. Ideally, studies should discuss displacement benefits in line with the current trends. Moreover, expanding geographical boundaries in research, particularly with a focus on regions such as Africa, could help broaden the understanding of FLW's role globally. Additionally, certain food groups remain underrepresented in current studies, and future research should aim to explore a wider variety of food waste streams to better understand their potential as feed. Finally, as interest in reducing FLW grows, and its application as feed is considered, it is essential that this is accompanied by the development of robust policies, regulations and safety directives that ensure the protection of public health and animal welfare, while fostering innovation. These frameworks will play a crucial role in enabling the scaling up of FLW use as livestock feed and ensuring its practical, safe application in the future.

## 5 Conclusions

The present systematic review contributes to the study of the sustainability of circular strategies for FLW introduced in livestock systems. This research demonstrates a growing interest in the topic over the years, revealing its increasing relevance in the academic field of sustainability. Furthermore, the majority of reviewed literature is concentrated in Europe, indicating the region's commitment to advancing research in this area. The methodological approaches utilized show heterogeneity of choices between consequential and attributional. There is a prevalence in accounting for further consequences through a hybrid approach but performing a full consequential life cycle analysis is still the least preferred method. Regarding LCT methods, similar to research on other domains, the focus predominantly lies on the environmental branch of sustainability. Economic and social sustainability continue to defy challenges in LCT research due to a lack of robust theoretical foundations and difficulties in obtaining high quality data (França et al. 2021). Additionally, while environmental impact categories are widely shared and utilised in the collected studies, economic and social aspects exhibit greater diversity and heterogeneity in indicators. Particularly, S-LCA has the potential to address specific issues within the food production not typically covered in the methodological guidelines (Sureau et al. 2018). The choice of LCT methodology significantly influences the research outcomes, specifically in addressing complexities of multifunctional systems. Complementary analysis methods are employed to address issues that LCT methods cannot, enriching our understanding of food waste management strategies. In conclusion, methodological disparities persist in studying the integration of FLW into livestock feeding through LCT methods, particularly in economic and social analyses. Moreover, we believe that the topic of this review needs to be addressed from a holistic perspective, calling for further research to validate findings and foster comprehensive policy development and informed decision-making.

To continue improving the sustainability of the food production chain, current circular economy strategies need further promotion, besides exploration of innovative measures. Our study investigated how food waste can contribute to livestock feed, considering its sustainability impacts through the life cycle thinking framework. Using the PRISMA methodology, we conducted a rigorous analysis of the existing literature on this topic. By carefully analysing relevant studies, we have identified the key methodological aspects studied across the literature. Our review also points out areas requiring more research for better understanding and implementation of this practice, such as the transparency and reliability of the methods for performing product displacement and the selection of social impact categories. However, challenges persist, such as the limited existing literature for the economic and social sustainability aspects. This has hindered the robustness of our findings in these areas. Additionally, ensuring food safety for animals and complying with current regulations places significant constraints, despite evidence supporting the potential benefits. Overall, examining the broader implications of using food waste in livestock feeding contributes to making our food system more sustainable.

## Appendix 1

**Table 4** List of articles included in the systematic review

| ID | Authors | Title |
|---|---|---|
| [1] | Salemdeeb et al. (2017) | Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options |
| [2] | Eriksson et al. (2015) | Carbon footprint of food waste management options in the waste hierarchy – a Swedish case study |
| [3] | Renouf et al. (2008) | An environmental life cycle assessment comparing Australian sugarcane with US corn and UK sugar beet as producers of sugars for fermentation |
| [4] | Vandermeersch et al. (2014) | Environmental sustainability assessment of food waste valorization options |
| [5] | Kim et al. (2011) | Evaluation of food waste disposal options by LCC analysis from the perspective of global warming: Jungnang case, South Korea |
| [6] | Lee et al. (2007) | Evaluation of environmental burdens caused by changes of food waste management systems in Seoul, Korea |
| [7] | San Martin et al. (2016) | Valorisation of food waste to produce new raw materials for animal feed |
| [8] | Takata et al. (2012) | The effects of recycling loops in food waste management in Japan: Based on the environmental and economic evaluation of food recycling Miki |
| [9] | Gnansounou et al. (2015) | Comparative techno-economic assessment and LCA of selected integrated sugarcane-based biorefineries |
| [10] | Moult et al. (2018) | Greenhouse gas emissions of food waste disposal options for UK retailers |
| [11] | Tufvesson et al. (2013) | Environmental performance of biogas produced from industrial residues including competition with animal feed e life-cycle calculations according to different methodologies and standards |
| [12] | González-García et al. (2015) | Life cycle assessment of pigmeat production: Portuguese case study and proposal of improvement options |
| [13] | Laso et al. (2018) | Combined application of life cycle assessment and linear programming to evaluate food waste-to-food strategies: seeking for answers in the nexus approach |
| [14] | Gassara et al. (2011) | Pomace waste management scenarios in Quebec-Impact on greenhouse gas emissions |
| [15] | Nhu et al. (2016) | Environmental impact of non-certified versus certified (ASC) intensive Pangasius aquaculture in Vietnam, a comparison based on a statistically supported LCA |
| [16] | Albizzati et al. (2019) | Valorisation of surplus food in the French retail sector: environmental and economic impacts |
| [17] | Khounani et al. (2021) | Environmental life cycle assessment of different biorefinery platforms valorizing olive wastes to biofuel, phosphate salts, natural antioxidant, and an oxygenated fuel additive (triacetin) |
| [18] | Canellada et al. (2018) | Environmental impact of cheese production: a case study of a small-scale factory in southern Europe and global overview of carbon footprint |
| [19] | Bais-Moleman et al. (2019) | Assessing the environmental impacts of production- and consumption-side measures in sustainable agriculture intensification in the European Union |
| [20] | Albizzati et al. (2020) | High-value products from food waste: an environmental and socio-economic assessment |
| [21] | Ledgard et al. (2020) | Temporal, spatial, and management variability in the carbon footprint of New Zealand milk |
| [22] | Parker (2018) | Implications of high animal by-product feed inputs in life cycle assessments of farmed Atlantic salmon |
| [23] | Ogino et al. (2007) | Environmental impact evaluation of feeds prepared from food residues using life cycle assessment |
| [24] | Albizzati et al. (2021) | A quantitative sustainability assessment of food waste management in the European Union |
| [25] | Lin et al. (2021) | An integrated life cycle multi-objective optimization model for health-environment-economic nexus in food waste management sector |
| [26] | Scherhaufer et al. (2020) | Environmental assessment of the valorisation and recycling of selected food production side flows |
| [27] | Wang et al. (2019) | Life cycle assessment of 36 dairy farms with by-product feeding in Southwestern China |
| [28] | Henriksson et al. (2014) | Carbon footprint and land requirement for dairy herd rations: impacts of feed production practices and regional climate variations |
| [29] | Stone et al. (2020) | Selection of sustainable food waste valorisation routes: a case study with barley field residue |
| [30] | Bundgaard et al. (2014) | Assessment of the potential of digestibility-improving enzymes to reduce greenhouse gas emissions from broiler production |
| [31] | Ogino et al. (2012) | Life cycle assessment of animal feeds prepared from liquid food residues: a case study of rice-washing water |
| [32] | Brehmer & Sanders (2008) | Implementing an energetic life cycle analysis to prove the benefits of lignocellulosic feedstocks with protein separation for the chemical industry from the existing bioethanol industry |
| [33] | Cortés et al. (2021) | Multi-product strategy to enhance the environmental profile of the canning industry towards circular economy |
| [34] | Quintero-Herrera et al. (2021) | The use of broccoli agro-industrial waste in dairy cattle diet for environmental mitigation |
| [35] | Gosalvitr et al. (2021) | Integrating process modelling and sustainability assessment to improve the environmental and economic sustainability in the cheese industry |

**Table 4** (continued)

| ID | Authors | Title |
|---|---|---|
| [36] | Morgan et al. (2021) | Thirsty work: assessing the environmental footprint of craft beer |
| [37] | Houssard et al. (2021) | Allocation is not enough! A system boundaries expansion approach to account for production and consumption synergies: the environmental footprint of Greek yogurt |
| [38] | Ríos-Fuentes et al. (2022) | Life cycle assessment of frozen broccoli processing: Environmental mitigation scenarios |
| [39] | Bunchai et al. (2017) | Life cycle greenhouse gas emissions of palm oil production by wet and dry extraction processes in Thailand |
| [40] | Teigiserova et al. (2022) | Circular bioeconomy: Life cycle assessment of scaled-up cascading production from orange peel waste under current and future electricity mixes |
| [41] | Kokemohr et al. (2022) | Life cycle sustainability assessment of European beef production systems based on a farm-level optimization model |
| [42] | de Souza et al. (2022) | Techno-economic and environmental assessment of bioenergy and livestock integrated systems in Brazil |
| [43] | Pelaracci et al. (2022) | Agricultural co-product management: an LCA perspective on the use of safflower oilcake from bio-oil production in Umbria region, Italy |
| [44] | Ibáñez-Forés et al. (2023) | Environmental implications of reprocessing agricultural waste into animal food: an experience with rice straw and citrus pruning waste |
| [45] | Misra et al. (2023) | Re-thinking water use in pig diets while accounting for food-feed competition |
| [46] | Shurson et al. (2022) | Environmental impacts of eco-nutrition swine feeding programs in spatially explicit geographic regions of the United States |
| [47] | Pardo et al. (2016) | Greenhouse-gas mitigation potential of agro-industrial by-products in the diet of dairy goats in Spain: a life-cycle perspective |
| [48] | Campos et al. (2020) | Life-cycle assessment of animal feed ingredients: Poultry fat, poultry by-product meal and hydrolyzed feather meal |
| [49] | Jain & Gualandris (2023) | When does upcycling mitigate climate change? The case of wet spent grains and fruit and vegetable residues in Canada |
| [50] | de Vries et al. (2019) | Entry points for reduction of greenhouse gas emissions in small-scale dairy farms: looking beyond milk yield increase |
| [51] | San Martin et al. 2021) | Multi-criteria assessment of the viability of valorising vegetable by-products from the distribution as secondary raw material for animal feed |
| [52] | Alba-Reyes et al. (2023) | Life cycle environmental impacts of using food waste liquid fodder as an alternative for pig feeding in a conventional Cuban farm |
| [53] | van Hal et al. (2019) | Accounting for feed-food competition in environmental impact assessment: towards a resource efficient food-system |
| [54] | Rodrigues Viana et al. (2023) | Life cycle assessment of oat flake production with two end-of-life options for agro-industrial residue management |
| [55] | zu Ermgassen et al. (2016) | Reducing the land use of EU pork production: where there's swill, there's a way |
| [56] | Møller et al. (2023) | Circularity indicators and added value to traditional LCA impact categories: example of pig production |
| [57] | Vogel et al. (2019) | Production of exotic fish and Brazilian hybrids in similar conditions: are there considerable differences of environmental performance? |
| [58] | Oldfield et al. (2017) | A life cycle assessment of biosolarization as a valorization pathway for tomato pomace utilization in California |
| [59] | Rasines et al. (2023) | Optimizing the environmental sustainability of alternative post-harvest scenarios for fresh vegetables: a case study in Spain |
| [60] | Escobar Palacio et al. (2020) | Exergy and environmental analysis of a polygeneration system of alcohol industry |
| [61] | Palmieri et al. (2017) | Environmental impacts of a dairy cheese chain including whey feeding: An Italian case study |
| [62] | Cimini & Moresi (2021) | Circular economy in the brewing chain |
| [63] | Xue et al. (2019) | Efficiency and carbon footprint of the German meat supply chain |
| [64] | Thakur et al. (2021) | A multidisciplinary approach for improving resource efficiency in the Indian surimi supply chain |
| [65] | Frasnetti et al. (2023) | Integrating insects into the agri-food system of northern Italy as a circular economy strategy |
| [66] | Budihardjo et al. (2023) | Comparative study of the life cycle assessment model for agricultural solid waste management: case studies in East Ungaran and West Ungaran districts, Semarang |
| [67] | Melas et al. (2023) | Circular bioeconomy practices in the Greek pig sector: the environmental performance of bakery meal as pig feed ingredient |
| [68] | dos Santos et al. (2023) | Reducing the environmental impacts of Brazilian chicken meat production using different waste recovery strategies |

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## Declarations

**Conflict of interest** The authors declare no competing interests.



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