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Review: Nutritional, production, and safety aspects of converting food loss and waste into feed for livestock

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Highlights

- Many nutrients leak from the food system in the form of food loss and waste.
- Food loss and waste can be alternative feed sources for livestock and insects.
- Food loss and waste can be substrates for single-cell protein production.
- Use of food loss and waste necessitates feed quality and safety evaluations.
- Recycling food loss and waste reduces extra natural resource and ingredient input.

Abstract

Agricultural activities place pressure on the environment through the demand of land, water, and nutrients, as well as the subsequent potential generation of emissions and pollutants. However, agriculture is essential to feed the growing population. Nutrient leakage from the food system in the form of **food loss and waste (FLW)** makes food production inefficient. The FLW refers to the deterioration of food quality anywhere in the food system that makes it unsuitable for human consumption. This includes vegetable and fruit leftovers, bakery leftovers and former foodstuffs products and properly processed food waste, depending on the legislation. A one-nutrition approach advocates for repurposing FLW into feed, thereby reducing nutrient leakage and food-feed competition. However, the evaluation of FLW in feed to produce a clear guideline for feeding FLW to livestock is not yet well established. Therefore, this review examines the use of FLW as a direct feed for livestock and FLW biotransformation via insects or microbes. These scenarios were evaluated based on their nutritional value and impact on livestock health, performance, and safety. After minimal to moderate processing of FLW, direct feeding offers a safe, nutrient-rich, and economically viable option for feeding FLW to livestock. Insects and microbes biotransform FLW into protein- and energy-rich biomass, providing macronutrients and supporting livestock performance under well-designed diet formulations and conditions. However, safety issues such as the presence of contaminants, spoilage and microbial risk in FLW can negatively impact livestock health and performance. Hence, beyond nutritional values, assessing the safety of using FLW as feed is mandatory, as discussed in this review. As of now, a full replacement of ingredients such as corn or soy is not possible due to a decrease in livestock performance in some instances and limitations in regulatory guidelines and infrastructure. This review proposes a categorisation of FLW based on the intensity of processing required to inactivate pathogens in the raw FLW, nutritional value, moisture content, logistics, and target species. The proposed categorisation offers a decision-making guideline for including FLW in feed. Further research is needed to prioritize a comprehensive assessment of the economic and environmental impacts of FLW use before reconsidering regulatory frameworks and substantially replacing conventional forage crops.

Keywords: Sustainability, one-nutrition, leftovers, black soldier fly, single-cell proteins

Implications

Food loss and waste can be recycled directly as animal feed or as substrate for producing insect meal and single-cell proteins for livestock feed, allowing nutrients that would otherwise be wasted to be retained in the food chain. Optimal food loss and waste utilization can be facilitated through proper categorisation of food loss and waste materials. The resulting environmental and social benefits include preventing nutrient leakage and reducing dependence on human-edible materials.

Introduction

Sustainable food production is crucial for feeding the growing population with minimal environmental impact. Food production and supply inherently generate **food loss and waste (FLW)**, which refers to food biomass that has deteriorated in quality or quantity along the food supply chain or that for technical/logistical reasons is no longer available for human consumption (FAO, 2019). This includes unused vegetable and fruit parts, **former food products (FFP)** such as bakery leftovers, leftovers from the agri-food production, as well as those from retail, restaurants, and household (García-Rodríguez et al. 2019). Hence, FLW cover a broad spectrum of materials with substantial intrinsic differences. According to the Food and Agriculture Organisation of the United Nations (FAO), around a quarter of the total food produced was lost or wasted globally along the entire supply chain between 2021 and 2023 (OECD/FAO, 2024). The FLW must be minimised, also considering the environmental pressure caused by agri-food production. Specifically, agriculture contributes 23% to anthropogenic **greenhouse gas emissions (GHGs**, IPCC, 2019), including direct on-farm emissions and indirect emissions from land use and forestry. Direct GHGs from agriculture are projected to increase by 6% in 2034, with livestock production estimated to contribute more than half of this increase (OECD/FAO, 2025). However, halving FLW is estimated to decrease the global agricultural GHGs emissions by 4% by 2030 (OECD/FAO, 2024). Another incentive to minimise FLW is that it helps to feed people sustainably. The United Nations Sustainable Development Goal target 12.3 aims to decrease global food waste by half and reduce food loss by 2030. Halving FLW is projected to decrease food prices, resulting in increased food intake and decreasing the number of undernourished people by 2030 (-26%, global average, OECD/FAO, 2025).

A shift in the food system toward sustainability implements a “one-nutrition” approach, aiming to reduce FLW while minimizing environmental pressures from agri-food production. This approach recycles nutrients across cropland, humans, and livestock—redirecting human-unsuitable food to livestock to prevent nutrient leakage (Pinotti et al., 2025). Livestock thereby supply essential macro- and micronutrients and restore soil organic matter. The circular model reduces resource use (land, water) without lowering food output (Schader et al., 2015; Govoni et al., 2023). Enhanced genetics, herd management, and nutrition boost feed conversion efficiency and yields (De Verdal et al., 2018; Pinotti et al., 2021b; Table 1). Thus, FLW as feed reduces nutrient leakage and reliance on human-edible crops (Pinotti et al., 2021a, 2025). While acknowledging the value of such an approach, there is still little debate about the logistical, economic, and legislative feasibility of massively implementing one-nutrition. To create synergies between cropland, animal, and human nutrition, a multidisciplinary platform is needed to bring together all the expertise required, from agriculture to human and animal health, including social sciences and economics. Subsequently, interconnecting the skills coming from the scientific sectors with those of the institutions and political decision makers would contribute to putting into practice this circular model (Makkar, 2016).

To upgrade FLW to feedstuff, geographical identification of FLW source and quantification of FLW biomass are mandatory. In addition, economic investments and supply-chain coordination between farmers and stakeholders are needed to redirect FLW from waste to feed. Local, small-scale recycling initiatives exist (Quintero-Herrera et al., 2023; Van Raamsdonk et al., 2023), but large-scale applications and economic assessments lag due to varying regional regulations—hindering uniform global implementation. Boosting knowledge on FLW nutrient features, safety and circular uses is key to aligning legislation locally/globally, making FLW economically competitive with primary feeds. This review will critically analyse three options to redirect nutrients from the FLW biomass back into the food system through livestock feeding: i) feeding FLW directly, ii) biotransforming FLW via insects, iii) biotransforming FLW via microbes to produce **single-cell proteins (SCP)**. In addition, a categorisation of different FLW materials based on their degree of processing is proposed, followed by a decision-making process for their optimal use as feed based on several factors.

Feeding food loss and waste to livestock

Within a one-nutrition approach, FLW can be converted into feed using different methods (Fig. 1). The easiest one is to feed the FLW directly to livestock. Fruit and vegetable leftovers or bakery leftovers can be fed to animals in their original form or after minimal processing, depending on safety features of the FLW material. The second method is to use insects fed on FLW with lower nutritional value or more complicated composition to be biotransformed before feeding livestock. This transforms FLW into a high-quality protein and lipid source in the form of insect meal. The final method is SCP production where FLW is used as a substrate for microbial fermentation to transform FLW into proteinous microbial biomass to be incorporated in animal feed. Due to historical human food safety concerns about parasites (e.g., *Trichinella spiralis* and *Toxoplasma gondii*) and bacteria (e.g., *Salmonella* and *Escherichia coli*) as well as attribution to catastrophic animal disease outbreaks (e.g., foot and mouth disease, Bovine Spongiform Encephalitis in ruminants, and the ongoing African swine fever), feeding uncooked or inadequately heat-processed FLW to livestock is not allowed (Shurson, 2025). So far, the traditional swill and garbage feeding is prohibited in many countries and the use of animal-derived FLW in animal feed is highly regulated. For instance, until the safety evaluation regarding processing conditions to inactivate prions and African swine fever virus is validated through appropriate research, ruminant-based processed animal protein should not be fed to ruminants and FLW containing pork and originated from countries with endemic African swine fever should not be fed to pigs (Shurson, 2025). Certainly, the use of FLW in feed is under strict regulations depending on the country. Some countries have legislation in place to actively support FLW recycling and promote safe and sustainable resource use. For example, Shurson et al. (2023) highlighted that countries such as Japan, South Korea, and Taiwan have been upcycling a large proportion of FLW into animal feed. The FLW is collected and mandatorily heat-sterilized to prevent microbial contamination, before feeding it safely to animals. The patented "Ecofeed" project of Japan is one such initiative. Here, the food waste is collected and transported in refrigerated vehicles to prevent spoilage and nutrient loss. The collected food waste is then heat-treated and sanitised depending on the intended species (Shimizu et al., 2020). In South Korea, FLW is processed to feed pigs, poultry, and aquaculture. Wet, dry, and fermented feeds are produced from FLW. Dry feed is produced by dehydrating food waste at 390 °C, whereas wet feeds are heat-treated at 80 °C for 30 minutes, followed by mixing with corn or rice husks to standardise the moisture concentration to 70-80% (Lee et al., 2024). Taiwan also has a zero-waste and resource recycling policy that supports the conversion of food waste into animal feed. In 2017, 60 to 75% of food waste was converted into pig feed (Tsai, 2020).

Unlike countries with active recycling policies, the USA and the European Union are more restrictive. In the USA, FLW has been fed to animals for many years. However, the quantity of FLW converted to feed is lower relative to the amount of FLW produced, which is also associated with a lack of infrastructure and economic incentives (Shurson et al., 2023). In Europe, the more restrictive legislations on FLW utilization were mainly driven by the Bovine Spongiform Encephalitis epidemic. Initiated by the United Kingdom in 1989, a ban on using rendered animal by-products in feed for all animal species was launched and was subsequently followed by the European Union in 2001 (Woodgate, 2023). Additionally, an abundant supply of corn and soybean meal, along with safety concerns, has limited the use of FLW in feed in both the USA and the European Union. Although certain recovered retail food, food processing waste, and restaurant food waste after proper treatments have been approved for use in animal feed, ambiguities in the guidelines for the types of FLW permitted and processing makes the industrial-scale conversion of FLW to feed still difficult (Shurson et al., 2023).

Europe produced 132 kg of food waste per inhabitant in 2022. Of this, the loss at the household level is the biggest, contributing up to 72 kg per inhabitant (Eurostat, 2022). This raises the need for increasing the upcycling of FLW into feed. Furthermore, in the European Union, FFP, a subcategory of FLW, is well-established and legally authorised as feed. The FFP includes wastes such as sweet and sugary bakery products, but not household and catering waste. In 2018, the European Commission issued guidelines for the use of food no longer intended for human consumption. Accordingly, FLW containing animal-derived foods should be processed under the combination of certain temperature, duration, and bar pressure before feeding them to livestock (Commission Notice, 2018), which requires additional infrastructure and energy inputs. These strict regulations related to the use of FLW as animal feed raise the issue of animal and public safety. Therefore, the application of FLW is restricted depending on the type of FLW and the pertaining legal framework. Considering this, only 5% of the FLW is converted into feed in Europe, and most of this is represented by FFP (Pinotti et al., 2021a). The following sections will elaborate the main methods to use certain FLW as feed. The nutritional value, effect on livestock performance, and safety aspects of each method will be considered.

Methodology and search strategy

This review focuses on three options to repurpose nutrients from FLW to the food system and it is conceived as a narrative review. Relevant literature was identified through searches in primary scientific databases using combinations of keywords related to the topic (Table S1). Based on this objective, the following four steps are applied to assemble relevant information regarding various FLW and their utilization in conventional livestock feeding, insect rearing, and SCP production: i) choosing types and origins of FLW sources with recent advances and/or findings, ii) choosing keywords for the literature search, iii) screening relevant literature using different databases, and iv) extracting information. These steps are further described below. The fruit and vegetable leftovers, bakery leftovers and FFP, **black soldier fly larvae (BSFL)**, and SCP were selected as focuses in this review as they: i) are recent trending subjects in animal nutrition, ii) do not compete resources used for other crop cultivation, which means that they are produced on non-arable land and are not a major driver of land use, iii) can be collected and recycled instead of ending up in fuel conversion, composting, landfill, etc., iv) do not result in products with human-edible grade, and v) could partially replace traditional nutrient sources in livestock diet or be provided as feed supplements according to studies on composition analysis, dietary inclusion rate of these materials, and results of the experimental trials.

The existing literature has been searched via databases of Google Scholar, Science Direct, Scopus, and PubMed. Initially, the information contained in the title and the abstract of each article was scrutinised to determine their relevance to the topic. The selection of articles was based on the following criteria: i) the article focuses on the use of the above-mentioned types of alternative feed sources in livestock diet, either as feed ingredients or as supplements, ii) the article indicates the inclusion level of the alternative feed and the final diet composition, and iii) the article contains analysis of the impacts of alternative feed-included diets on the animals, safety, economic, and/or the environment. Articles were eliminated after the selection process based on the following exclusion criteria: i) the article described the use of alternative feed without specifying the exact quantity of inclusion since the alternative feed was used in a form of premix with other extracts, additives, supplements, and/or other products, and ii) the article was not written in English and was untranslatable.

Case 1: Feeding food loss and waste directly to livestock

The FLW can be directly converted to feed with or without massive processing or bioconversion (e.g. microbial transformation) according to its safety evaluation. This includes a variety of materials, such as fruits and vegetable leftovers and FFP. One of the deciding factors of processing is the DM content of FLW. The FLW with high moisture content (or low DM), such as fruits and vegetable leftovers, can be directly incorporated into the diets of livestock. However, the higher moisture content in these FLW makes them prone to spoilage due to microbial and enzymatic activity. This aspect limits the stability and shelf life of moist FLW in feed (Pinotti et al., 2020). To overcome the issues of high moisture and decreased shelf life and stability, processing techniques such as drying, heat processing, fermentation or ensiling are used. Feeding FLW directly to livestock without any processing is the easiest method. However, this is possible only when the site of FLW production is close to the site of utilisation. High nutritional value and minimal contaminants, including pathogens, are other influencing factors. For instance, a survey in the Gamo Zone, Southern Ethiopia, reported that banana peels (100% of respondents) and sweet potato leaves (89.5%) are fed raw to livestock, often without slicing (Yohannes et al., 2025). In Sri Lanka, a survey of large-scale piggeries reported that FLW represented up to 82% of total feed provided to animals, usually in combination with concentrate feed. This type of FLW is supplied daily to keep it fresh, reduce spoilage, biological risk, and costs by maximising the volume of FLW transported and concentrating the sites of FLW collection. Furthermore, the geographical proximity between farms and FLW source plays a key role in reducing the cost of FLW recycling. Since regulations about FLW use as feedstuff are still lacking in Sri Lanka, majority of farmers (88%) declared that FLW is heat processed before being fed directly to pigs, although the processing conditions vary between farmers (Jayathilake et al., 2022). In some cases, FLW is previously sliced or dried before feeding livestock. This might help improve digestibility and reduce wastage by livestock. Products that are rejected from the food supply chain due to size or cosmetic reasons can also be repurposed as feed. For example, Díaz et al. (2025) observed that completely replacing corn with discarded carrots (16% DM inclusion rate) did not affect rumen pH and the production of volatile fatty acids, ammonia, and methane in dairy sheep (Díaz et al., 2025). Therefore, repurposing FLW as animal feed makes it possible to reduce the reliance on human-edible ingredients such as corn.

Fermentation is the second direct method for feeding FLW to livestock. This method helps to store the feed longer without spoilage, which is particularly advantageous for easily perishable FLW (Torsabo et al., 2026). For instance, pineapple waste fermented as silage could replace 25% of Napier grass silage for cows without affecting their final body weight (Kyawt et al., 2020). However, an increased DM intake was noticed to compensate for the lower nutrient contents in pineapple silage relative to Napier grass silage. Despite this finding, substituting classic feed ingredients with fermented FLW in livestock diets is a way to improve the sustainability of animal feeding. Fermentation can also be done to improve the nutritional value of the FLW (Torsabo et al., 2026). For instance, nutrient-poor palm kernel cake was co-fermented using bacteria *Lactobacillus plantarum QZSL* and yeast *Saccharomyces boulardii mafic-1701* to improve their nutritional value. The fermented palm kernel cake increased CP levels by 2% (as-fed basis) and reduced sugars by 35 mg/g. The fermented palm kernel cake in the diets of male Cobb broilers did not affect their growth (Liu et al., 2025). This also underscores the need to verify the nutritional value of FLW, the effect of FLW on the performance of livestock, and safety aspects when using FLW as feed, which is elaborated in the following sections.

Moderate processing is performed on FLW with low moisture content. For example, FFP, which is usually dry, undergoes a series of processing steps to become feed. Most of the FFP has a packaging wrapping, therefore, the FFP is first unwrapped and then coarsely ground. Since some packaging residues may remain in the raw FFP, the packaging pieces are further removed by sieving and wind sifting, as described in Van Raamsdonk et al. (2011).

The economic aspects of upgrading FLW to feedstuff are less explored, mostly due to the difficulty to retrieve standardised and clear data because of a poor theoretical foundation that does not support data collection (Goldáraz-Salamero et al., 2025). In one study, the economic benefits of converting FLW to livestock feed were discussed (Albizzati et al., 2021). In particular, the production of wet animal feed from FLW resulted in cost benefits thanks to energy and fertilizer substitution, although processing and transport factors may prevail (Albizzati et al., 2021), thereby underlining once again the importance of the processing rate of FLW to determine its cost effectiveness. In summary, the safety of FLW must be assessed before using it as feed. Depending on the FLW source, the degree of processing may vary.

Above all, direct feeding reduces the time interval between FLW collection and consumption and potentially the costs due to additional steps between the two.

Nutritional value of feeding food loss and waste directly to livestock

The FLW comprises diverse food types depending on the geographical location of FLW production, as well as the point at which the food material leaves the food chain becoming FLW. The diversity leads to varying nutritional values due to their innate properties, such as the type of products, storage conditions, and processing methods (Dou et al., 2018; Pinotti et al., 2023a). Furthermore, there is a lack of large-scale studies about the nutritional content and the seasonal variability of FLW, because diverse FLW items are difficult to compare on the same basis (Dou et al., 2018). Therefore, the huge variety of FLW is, on the one hand, a resource to meet the specific nutritional needs of livestock, but on the other hand represents a concern for its lack of univocal and comprehensive characterization. For instance, Pinotti et al. (2020) reviewed the nutrient composition of various crop salads, which are reused for feeding livestock. They have 6% DM, 36% NDF and 23% ADF compared with the 25% DM, 58% NDF and 39% ADF in fresh forage. The lower fibre content might increase the production of propionate in the rumen. Propionate production consumes hydrogen produced during fermentation, thereby restricting the availability of hydrogen for methanogens to produce methane from carbon dioxide (Beauchemin et al., 2009; Benchaar et al., 2014; Eslamizad et al., 2025). However, the CP level in crop salads is greater (21%) than that of fresh forage (8%). The increased CP level can increase the nitrogen emission but at the same time reduce the need for high-protein concentrate feedstuffs, although the quality of protein sources (e.g. amino acid content and profile) should be investigated. Another example of a specific FLW category is FFP. The nutrient composition of salty bakery leftovers, a type of FFP, is comparable to that of cereal grains (e.g. wheat and barley), as well as the energy content (between 15 and 20 MJ/k). However, FFP are usually higher in simple sugars and lipids (Pinotti et al., 2023b). Indeed, their average fat content is higher (10%) than wheat or barley (> 5%). In ruminants, the higher fat content of FFP can reduce feed fermentation because lipids act as antimicrobial factors, reducing microbial fermentation of carbohydrates (Jenkins, 1993).

The inconsistency in nutrient composition is still debated in the scientific community and is one of the decisive factors that influences farmers' decisions to use FLW and its commercialisation (Rajeh et al., 2021). Indeed, the variability in nutritional value requires a flexible feed formulation depending on the livestock species considered. Two provisional strategies are suggested below. One strategy is to blend multiple batches of FLW from different sources to an average nutritional content that complies with the animal's nutritional requirements. The second strategy is relying on local FLW from similar sources to reduce the variability between batches. Although, seasonality can influence the nutrient content of FLW sources. In any case, systematic sampling procedures and comprehensive analyses of nutritional content of multiple FLW batches could address this issue.

Effects of feeding food loss and waste on the performance of livestock

The FLW could substitute conventional plant-based feed ingredients of livestock without adversely affecting their performance (Pinotti et al., 2021a). For instance, 5% of corn starch in the diet of juvenile red tilapia (n = 360 animals) was replaced for 60 days with fruit leftovers, including pineapple skin, pineapple crown, jackfruit skin, jackfruit pulp, or grated coconut. The partial replacement did not cause any difference in the feed conversion ratio, except that the fish fed pineapple crown and jackfruit skin showed a reduction in body weight by 6 g (Sulaiman et al., 2022). In the same study, serum biochemical indices were either slightly increased or unchanged in fruit-fed animals compared to the control group. When similar diets were fed to Malaysian manseer (n = 300 animals) for 60 days, better results were found than those from red tilapia. The final body weight and body length increased in groups fed fruit wastes of pineapple skin, jackfruit pulp, or grated coconut without decreasing the fish's nutrient composition as the nutritional profile of fruit leftovers supported lipid and protein retention in the body. However, the palatability and the content of bioactive compounds of some fruit leftovers might have differentially affected the growth rates of the two fish species (Sulaiman et al., 2022). Regarding the FFP utilisation in aquaculture, Najim and Al-Tameemi (2023) conducted a study where up to 75% of corn and barley in the diets of two-week-old common carp (*Cyprinus carpio L.*) was replaced by FFP for 48 days. The FFP diet did not cause changes in final body weight or apparent digestibility coefficients of CP and crude fat. However, FFP significantly increased the apparent digestibility coefficients of DM and carbohydrates by 5%, possibly due to the higher availability of easily digestible carbohydrates in FFP. The improved digestibility was reflected in the nutrient composition of the fish, where the CP significantly increased by 2% while other nutrients remained unaffected (Najim and Al-Tameemi, 2023). These examples suggest that FLW, such as fruit waste or FFP, could partially replace conventional feed ingredients with a wide inclusion rate, without notable negative effects on the performance or health. However, the interspecific differences in response to the FLW inclusion may occur, considering the animal species, nutritional profile of FLW, and inclusion rate.

Poultry feed can also be modified with the incorporation of FLW. For instance, enzymatically treated and fermented palm kernel cake was used to replace corn by 10% in the broiler diet (Liu et al., 2025). The average daily gain and daily feed intake were improved in the broilers fed palm kernel cake. These outcomes might be resulted from the compensation of lower energy content in the diet to maintain an increased weight gain. In addition, the inclusion of processed palm kernels up to 10% did not affect the immune organ indices and serum antioxidant capacity of broilers (Liu et al., 2025). Similarly, replacing 40% of corn with FFP in Ross 308 broilers for 35 days did not affect their body weight gain, feed intake, or feed conversion ratio. The carcass weight and the weights of thighs, drumsticks, and wings also remained unaffected. However, eviscerated carcass and breast meat significantly decreased by 2 g/100 g of body weight, probably due to an unbalanced amino acid intake from FFP-included diets. Despite this, the authors reported that the FFP diet significantly decreased the feed cost per kg gain by 17% compared to the control diet, because corn had a higher feed cost than FFP in their case (Sirirotjanaput et al., 2025). These findings suggest that FLW could partially replace classic feedstuffs in the diets of poultry and, in some cases, be cost-effective.

In the case of pigs, replacing 30% of the cereals in the diets of post-weaned or growing-finishing pigs with FFP did not affect their growth performance, even though the apparent total tract digestibility was slightly increased by 2-4% (Tretola et al., 2019; Mazzoleni et al., 2023a). The carcass qualities such as carcass weight, length, and yield as well as the gut microbiota composition and faecal volatile fatty acid concentration also remained unaffected by the dietary inclusion of FFP (Tretola et al., 2022; Mazzoleni et al., 2023a). This shows that FFP can be used up to a considerable inclusion rate (30%) to replace cereals in swine nutrition without impairing their performance and health. Including FLW could reduce the reliance on natural resources in pig farming. Govoni et al. (2025) found that the demand for pig feed was 105.5 million tonnes in the European Union and the USA in 2018. Replacing 30% of conventional dietary energy sources, such as corn, barley and wheat in the pig diet with FFP reduced the demand for these sources by 29%. In addition, 4.2 and 1.1 million hectares of agricultural land in the European Union and the USA would be freed up. This replacement strategy also saved 27.6 km^3 of water resources. Therefore, it is suggested that including FLW in the pig diet not only reduces the reliance on conventional energy sources but also uses less land and water (Govoni et al., 2025).

Apart from the livestock species mentioned above, FLW can also be fed to ruminants to partially replace cereals without adverse effects on their performance. For instance, substituting 1.6 kg of corn and 0.3 kg of soybean in the diet of beef Limousin heifers with 1.5 kg biscuit leftovers and 1.5 kg wheat wet distiller's grains (as fed) during the fattening period (145 days) also did not affect the growth performance (Grossi et al., 2022). Similarly, when 11% of cereals in the diets of multiparous dairy cows (60 to 110 days in milk) were replaced by bakery food leftovers and distiller's wheat grain with solubles, the milk yield increased from 35.71 to 37.39 kg without alterations in the percentage of milk lactose, fat, and proteins. Meanwhile, the body weight, water intake, DM intake, daily average ruminal pH, rumination time, fibre digestibility, and molar proportion of volatile fatty acids were comparable to the control group (Mammi et al.,2022). Similar results have been obtained combining FFP and fresh grass-based diets in early lactating dairy cows (Reiche et al., 2025).

However, a major concern of feeding high-energy FLW like FFP to ruminants is the risk of ruminal acidosis. The high sugar content in FFP can be fermented rapidly by the rumen microbes compared with complex carbohydrates (Nayohan et al., 2024). The aforementioned study on Limousin beef heifers did not observe a significant difference in the incidence of rumen acidosis when soybeans and corn in the diet were partially replaced with biscuit leftovers and wheat wet distiller's grains (Grossi et al., 2022). Another study on Simmental cows (127-171 days in milk) fed with 30% of FFP instead of grains for 35 days also showed an increase in milk yield by 4 kg/day without developing ruminal acidosis. The duration of ruminal pH below the threshold of 5.8 in cows fed grains was 71 min/d longer than that observed in cows fed FFP (Kaltenegger et al., 2020). This reduced risk of ruminal acidosis could be due to the stage of lactation considered, which was rather advanced (see below). As reviewed by Tretola et al. (2025), high levels of sugar cause the activation of Na+/H+ exchangers on the rumen wall, facilitating an accelerated removal of volatile fatty acids from the rumen. For dairy buffaloes (111 ± 3.63 days in milk), feeding a commercial product containing 87% of biscuit meal instead of fresh sorghum for 90 days did not result in differences in feed intake, body condition score, milk yield, and gross milk quality (Neglia et al., 2023). These studies on cows and buffaloes suggest that FLW, including FFP, can partially replace cereals or green forages, depending on the type of FLW. However, it should be noted that the two above-mentioned studies used ruminants in mid or late lactation, with a relatively stable rumen environment. Therefore, dietary intervention during this period probably might have resulted in fewer observable side effects, especially the risk of sub-acute ruminal acidosis. Hence, the health consequences of feeding FLW containing higher amounts of rapidly fermentable carbohydrates throughout the entire lactation must be understood. To sum up, the nutritional features of FFP are comparable to that of conventional cereals, but different FLW categories with other features might provide different outcomes. For instance, fruit and vegetable leftovers are a FLW category more related to seasonality, bulkiness, and high moisture content than FFP. They have been reported to reduce ruminal nutrient digestibility at greater inclusion rates, probably due to the higher indigestible fibre contents and the presence of phenolic compounds that hinder the enzymatic degradation of nutrients in rumen. Despite this, most studies found no relevant effects on milk yield and milk composition when including fruit and vegetable FLW in ruminant diets (Jalal et al., 2023).

Therefore, nutritional characteristics and seasonality, linked to compositional variability, as well as the inclusion rate of different FLW categories used to replace conventional feeds in livestock diets appear to be the most critical factors in evaluating the effects of FLW dietary inclusion on animal health and performance.

Safety concerns of feeding food loss and waste directly to livestock

Regulations on FLW use as feed and processing conditions are major bottlenecks for large-scale real-world implementation. Worldwide regulatory frameworks vary, with processing requirements differing intra- and internationally, and depending on FLW categories approved as feedstuffs. In general, timely collection and correct management procedures should be guaranteed to reduce the risk of spoilage of FLW (Dou et al., 2018). Safety concerns of all types of FLW have not been addressed in the same way due to their broad spectrum of sources and origins. When the supply chain/availability of specific FLW sources is more robust, the related safety information is more consistent. In the case of FFP, they undergo unpacking, mixing, grinding, and drying after being collected, thus influencing their safety (Lin et al., 2024). Packaging remnants and microbial load are two of the major safety concerns of using FFP in feed (Tretola et al., 2017). Plastics (polyolefin), aluminium foil, paper, and paperboard are the common packaging materials used in FFP and packaging remnants constituted by these materials were actually detected in FFP. In the study of Mazzoleni et al. (2023b), 4 to 19 particles of packaging remnants were discovered per 20 g fresh FFP sample. Although such amounts of packaging remnants still meet the current and generally accepted allowance level for physical contaminants in feed materials which ranges from 0.125% w/w up to 0.2% w/w (Tretola et al., 2025), further investigation on legacy pollutants related to these packaging remnants is warranted (Lin et al., 2025). Among different packaging materials, plastics raise greater concerns. This is because plastics is the most commonly used food packaging material (Lin et al., 2024) and over 4200 chemical substances used in the plastic manufacturing have been identified as hazardous (Rekibi et al., 2025). Moreover, fragmented plastics can further turn into micro- and nano-plastics and be accumulated in the food chain as legacy pollutants disturbing feed and food safety and the ecosystem (Eichinger et al., 2024).The total viable count of microbial load in analysed FFP samples composed of confectionary products, bakery leftovers, and sweet snacks was all under 6 Log CFU/g, the generally recognized risk-of-spoilage threshold (Tretola et al., 2017). The counts of several pathogenic bacteria and fungi were below the legislative threshold as well, and the samples were free of *Salmonella* spp. (Tretola et al., 2017). For instance, the acceptable threshold limit established in the animal feed sector for the count of *Enterobacteriaceae* is < 10 Log CFU/g (European Regulation (EC) No 142/2011), for that of *Bacillus cereus* and its spores and other potential pathogenic aerobic microorganism is < 5 Log CFU/g where toxin production may be started if exceeding such concentration, and for that of *Clostridia* is < 4 log CFU/g but < 1 Log CFU/g is considered more satisfactory (Tretola et al., 2017). Overall, heat treatments on FFPs (e.g., cooking, extrusion, baking) ensure safety as feed ingredients, aided by minimal packaging residues and low microbial loads. These factors pose no implementation bottlenecks since monitoring suffices for safety.

A further issue addressed by Mercogliano et al. (2025) is the presence of naturally occurring methylxanthines in FFP containing cocoa and chocolate products. Methylxanthines such as theobromine and caffeine possess a significant toxicological concern that may limit their use when present in high concentrations. The EFSA Scientific Opinion of the Panel on Contaminants in the Food Chain (2008) reported that theobromine showed growth retardation, diarrhoea and lethargy in pigs over-exposed to higher doses of theobromine. In FFP, other contaminants, such as heavy metals (e.g. Al, As, Cd, Pb), persistent organic pollutants including polychlorinated biphenyls, and other dioxins, showed no detrimental safety issues (Lin et al., 2025). This is confirmed by both short-term (42 days) and long-term (110 days) studies where the use of FFP did not compromise the performance, health and welfare of pigs (Manoni et al. 2024 and 2025).

Beyond FFP, nitrate accumulation in FLW like salad crops and baby leaves poses safety risks, especially for ruminants. In the rumen, nitrates convert to nitrites and ammonia. Excess absorption of nitrites and ammonia forms methemoglobin from hemoglobin, inhibiting oxygen transport and causing methemoglobinemia. Accurate nitrate monitoring in feed is crucial to prevent poisoning (Pinotti et al., 2020).

Other categories of FLW that are more complex in their composition are household and catering waste. Between 2020 and 2023, household waste accounted for 53% of the total food waste generated in the EU, while restaurant waste was 14% (Eurostat, 2025). However, their use in feeding livestock is prohibited in the EU because of the potential presence of undesirable substances and biological hazard (Boumans et al., 2022). García et al. (2005) compared different waste streams (meat and fish waste, plant waste, restaurant waste, and household waste) and observed a balanced nutritional composition for household waste compared to the other waste streams, thus hypothesizing its potential application in feed. Although heating household waste at 65 °C for 20 min makes it microbiologically safe, the detected presence of undesirable elements (Pb and Cd) hinders its inclusion in livestock diets. Then, the use of catering waste as feed was reviewed by Georganas et al. (2022). The high moisture content of catering waste is favorable for microbial growth, therefore heat treatment is mandatory to reduce the risk associated with the uncontrolled spread of harmful microorganisms. Chemical (e.g., heavy metals) and physical (e.g., non-edible materials) contamination hinder operational use of catering waste as feed. Practical conversion challenges persist, barring its inclusion in EU-allowed feed materials.

In summary, although not all types of FLW used in livestock nutrition have been systematically studied as FFP, some have already demonstrated high standards of quality and safety, suggesting their potential in replacing conventional feed ingredients. Instead, other FLW categories such as household and catering waste still require further research and validation to make them compliant to feed regulations.

Case 2: Feeding food loss and waste to insects

Insects are the second option for redirecting FLW into the food system since they are omnivores, take up less space, and can survive on substrates with high diversity. As reported by Pinotti and Ottoboni (2021), insects are able to biotransform low quality or fibre rich FLW to energy and protein rich biomass suitable for feed. The most common insects used in feed are **black soldier fly (BSF**; *Hermetia illucens*), common housefly (*Musca domestica*), yellow mealworm (*Tenebrio molitor*), and cricket (*Acheta domesticus*; Veldkamp and Bosch, 2015). The BSF is the most studied insect as a protein source in aquaculture, poultry, and pig nutrition. This review focuses on BSFL to illustrate the potential of insects in biotransforming FLW into feed, thanks to their capacity to colonise and biotransform decomposing organic waste using their enteric amylases, proteases, and lipases (Kim et al., 2011). The following sections evaluate the nutritional value of BSFL, the impact of adding FLW-reared BSFL in livestock diets, and the safety of BSFL inclusion.

Nutritional value of black soldier fly larvae

The BSFL serves primarily as a protein source in feed. The CP levels range from 216 to 665 g/kg in defatted BSFL and average 439 g/kg in full-fat BSFL. These values are competitive with soybean meal (494.4 g/kg) and fishmeal (675.3 g/kg). In contrast, the crude fat levels in BSFL exceed those of conventional feed sources, ranging from 46 to 98.5 g/kg in defatted BSFL and from 294 to 514 g/kg in full-fat BSFL. Both ranges are higher than those of soybean meal (14 g/kg) and fishmeal (103.6 g/kg; Lu et al., 2022). The amino acid profile of dried BSFL shows less variability even when different rearing substrates are used (Barragan-Fonseca et al., 2017). Specifically, BSFL are rich in lysine (average 38.8 g/kg), and the levels of other essential amino acids such as leucine (average 44.6 g/kg), phenylalanine (average 33.0 g/kg), and threonine (average 26.7 g/kg) are comparable to those of soybean meal (Lu et al., 2022). In addition, the percentage of saturated fatty acids accounts for 45%-76% of the total fatty acids in BSFL (Ewald et al., 2020). This higher level of saturated fatty acids is undesirable as it can increase saturated fat content (Schiavone et al., 2017). Further, BSFL are also characterised by high levels of lauric acid, the predominant metabolite of lipid metabolism in BSFL (Spranghers et al., 2017). Being a medium-chain fatty acid, lauric acid contributes to prebiotic and antibacterial activities important for animal gut health (Devi and Kim, 2014).

The nutrient composition of insects is influenced by the type of substrates. The BSFL can grow in a variety of substrates, but with varying efficiency (Lalander et al., 2019). The BSFL development is related to the level of proteins and fat in the substrate (Nguyen et al., 2013; Spranghers et al., 2017), influencing their growth, survival, and nutrient composition. For instance, the BSFL reared on wheat bran and millet waste had higher levels of CP (41%) compared to restaurant leftovers (37.6%) or fruit waste (36.2%). Similarly, ether extracts of BSFL reared in wheat bran (30%) were higher than restaurant leftovers or fruit waste by 6%, but less than millet waste by 4%. This variation of nutrient composition in BSFL based on their substrates was also reflected in other nutrients such as ash, nitrogen-free extract, metabolizable energy, and mineral contents (Opoku et al., 2023). Therefore, the type of substrates used for rearing insects is important and the resulting variation in nutrient composition of insects must be factored in, especially when using FLW (Pinotti and Ottoboni, 2021). In addition, the BSFL tend to accumulate minerals present in the substrate. Moradei et al. (2025) demonstrated that the BSFL grown in an okara and potato-based substrate fortified with selenium and zinc accumulated these elements in their biomass. This shows the potential of using BSFL as a mineral supplement in livestock.

Effects of black soldier fly larvae on livestock performance

The inclusion of BSFL in feed does not adversely affect the performance or health of livestock in aquaculture, poultry, and pig production. For instance, the consequences of 35% inclusion (on DM basis) of BSFL reared in a strawberry or spent grain substrate were studied in a zebrafish model (Sangiacomo et al., 2025). The inclusion of BSFL meal neither negatively affected the growth rate nor the health of zebrafish. Instead, it improved the cumulative body weight gain of zebrafish by 29% to 36%. As evidenced by the consistent macrophage and neutrophil densities, the BSFL meal did not cause gut inflammation and there was no increase in the expression of a panel of inflammatory marker genes. Finally, the reproductive performance of zebrafish was not affected by the inclusion of BSFL meal, as evidenced by the lack of significant differences in the number of eggs, hatching rate, and larval survival (Sangiacomo et al., 2025). Beyond laboratory models, replacing plant proteins from the diet of Atlantic salmon with 10% BSFL did not affect the proximate composition of the fish. The meat quality traits, such as the skin colour and firmness of the salmon fillets also remained unaffected by the BSFL (Farris et al., 2026). Therefore, BSFL could be partially included in aquaculture feed without decreasing the performance or compromising the health of aquaculture species.

The BSFL are also a suitable alternative protein for poultry. For instance, broilers (Cobb 500 fast feathering) fed up to 12% BSFL (as-fed basis) for the first 21 days did not negatively affect body weight and body weight gain. However, the feed efficiency decreased on day 21. The feed-to-gain ratio of broilers fed the diet containing 12% BSFL was significantly higher than that of broilers fed the diet without BSFL (1.31 vs 1.27) on day 21. Such increase in feed-to-gain ratio could be due to the increased levels of inert fillers, such as sand, added in the BSFL diet. Nevertheless, the persistence of these effects beyond 21 days was not investigated in this study (Dillard et al., 2025). Similarly, inclusion of 5% BSFL (as-fed basis) in the diets of female Muscovy ducks from 3 to 55 days of age did not affect their growth and slaughter performance (Gariglio et al., 2025). Further, turkeys fed 5% BSFL for 105 days grew as well as the control group and the mean relative abundance of cecal microbiota composition, at the phylum and genus level, of these turkeys on the day of slaughter remained unaffected (Zampiga et al., 2025). Therefore, partial inclusion of BSFL seems not to adversely affect the performance and health of poultry.

Regarding pigs, the inclusion of BSFL in creep and nursery diet for weaners did not have adverse effects on growth performance and health parameters, including gut morphology, haematological, and immunological parameters (Driemeyer, 2016; Crosbie et al., 2021). Additionally, replacing fish meal with BSFL meal in the diet of growing-finishing pigs increased the average daily gain, carcass weight, and pork quality (Chia et al., 2021; Zhu et al., 2022). Yang et al. (2025) found that replacing 15% of corn and soybean meal in growing pigs with BSFL (as-fed basis) did not change the apparent total tract digestibility of energy, metabolizable energy, ether extract, and crude fibre. However, the apparent total tract digestibility of DM, CP, NDF, and ADF was decreased by 2-7%. This decrease in the digestibility could be associated with the presence of chitin in the BSFL. Including chitinase, an enzyme that degrades chitin, can restore the decreased apparent total tract digestibility of DM and CP (Yang et al., 2025). Feeding Danube white pigs with 120 g/kg BSFL in the diet from 39 days increased reactive oxygen species and inflammatory markers, such as cytokines (Yordanova et al., 2025). This could be explained by a physiological response to the new BSFL diets, highlighting the need to study the long-term consequences of BSFL inclusion in pigs.

The BSFL could be an alternative to conventional feed for ruminants. However, it is legally prohibited in areas such as the European Union, following the Bovine Spongiform Encephalopathy outbreak in the 1990s. Nevertheless, BSFL is a great source of proteins and lipids for ruminants. For instance, Valdostana Red Pied cows (parity = 3 and 68 days in milk) were fed 3% of BSFL oil instead of palm oil for 50 days. The BSFL oil is the lipid extract of BSFL that is rich in lauric acid, linoleic acid, oleic acid, and palmitic acid. Inclusion of BSFL oil did not affect the total nutrient intake and no difference was observed in the apparent total tract digestibility as well as in plasma parameters and serum antioxidant capacity. Cows fed BSFL oil had 0.8 kg more milk yield per day (20.3 kg/cow/day vs 19.5 kg/cow/day), but no change in the milk composition relative to cows fed hydrogenated palm oil (Rastello et al., 2025). Besides, the presence of lauric acid in BSFL oil could be used as a potential replacement of palm oil or coconut oil in milk replacer for dairy calves. Holstein calves fed up to 40% of BSFL oil showed no difference in calf growth (final body weight and average daily gain), feed efficiency, change in wither height, or scour days in the first 10 weeks of life (Quigley et al., 2025). For pre-weaned goats, providing them milk replacer containing BSFL neither impaired their growth nor health (Sepriadi et al., 2022). In addition to the oil, defatted BSFL meal was fed to lactating Holstein-Friesian cows to replace soybean meal for 18 days (Braamhaar et al., 2025). A 50% replacement did not affect the DM and organic matter intake of the cows whereas a full replacement did decrease the amount of these intakes (16.6 and 15.1 kg/d vs 17.6 and 16.2 kg/d, respectively) compared to cows fed non-replaced diets. The CP intake was decreased due to BSFL inclusion. However, the milk yield and the composition remained unaffected (Braamhaar et al., 2025).

In vitro studies on the ruminal fluid revealed a decrease in methane levels from 24 mM to 13 mM upon supplementation with 8% BSFL oil (% DM). The ruminal pH, total ammonia-nitrogen, and protozoal population remained unaffected with the BSFL oil supplementation after 48h-incubation (Albarki et al., 2025). This could be linked to the decreased substrates for methanogenesis and decreasing microbial activity due to BSFL oil. Finally, the BSFL could also be used as a protein supplement in beef cattle foraging in low-quality grass (Fukuda et al., 2022). These studies on ruminants suggest the benefits of using BSFL as an alternative protein and fat source. However, the safety aspect must be addressed and reconsidered for their use in ruminants (Pinotti et al., 2023a). In addition, there must be a standardisation in the inclusion protocol of BSFL in ruminant feed.

Safety concerns of feeding black soldier fly larvae

Bioaccumulation is a bottleneck for large-scale utilization of insects, although monitoring the concentration of contaminants in the substrate for raising insects is a valid solution to reach implementation. The BSFL ingest heavy metals in the substrate and can bioaccumulate them, possibly causing detrimental effects on the health of livestock. For example, chronic Cd exposure causes oxidative damage and injury to chicken hepatocytes and nephrocytes (Ge et al., 2019; Wang et al., 2026), plus inflammation and apoptosis in bovine mammary cells (Chen et al., 2021). Thus, sustained Cd harms vital organ function. Moreover, livestock may transfer these heavy metals into food products of animal origin, which could threaten human health (Iram et al., 2025). The extent of accumulation depends on the concentration of heavy metals in the substrate. Heavy metals, including Cd, Pb, and As, were detected in the substrates authorised for BSFL by the EU. These substrates include FLW such as wheat bran, carrots, and apricots. Concentrations of these heavy metals in the substrates vary between 74.1 and 81.8 µg/kg of Cd, 22.7 and 39.2 µg/kg of Pb, and < 10 µg/kg of As on a DM basis. The detected values were within the maximum limits in complete feed authorised by the EU, which are 568 µg/kg for Cd, 5682 µg/kg for Pb, and 2273 µg/kg for As on a DM basis (Council of the European Union, 2002). While these heavy metals were transferred from the substrate into the BSFL tissues, concentrations remained below the maximum limits in feed. For instance, As and Pb concentrations remained less than 1.4% of the maximum limits. However, Cd concentrations in the BSFL tissues were 544.5 µg/kg on a DM basis, representing 95.8 % of the maximum limit. This could be attributed to high levels of calcium in BSFL. The Cd^{2+} has an ionic radius similar to that of calcium ions. Therefore, Cd^{2+} competes with calcium ions for calcium channels and thereby facilitates the accumulation of Cd. Bioaccumulation of these heavy metals was quantified using the bioaccumulation factor (BAF) which represents the ratio of the concentration of a heavy metal in BSFL to that in the substrate, both expressed on a DM basis. The BAF values exceeded 1.0 for all heavy metals, reaching up to 6.7 for Cd, 1.4 for Pb, and 3.3 for As (Papin et al., 2026). This suggests that bioaccumulation of heavy metals occurs in BSFL reared on FLW substrates. Although these heavy metal concentrations were below the maximum limits, accumulation increased in response to higher substrate concentrations (Spranghers et al., 2025).

Pesticide residues are present in the substrates derived from FLW and are ingested by the BSFL. This raises concerns regarding the bioaccumulation of these residues in BSFL and their potential transfer to humans via livestock. For example, the pesticide chlormequat was detected in the BSFL tissues reared in apricot substrate (Papin et al., 2026). Spranghers et al. (2025) studied the bioaccumulation and uptake of pesticides from substrates in BSFL. Six-day-old BSFL were reared for 14 days in a substrate containing a cocktail of active ingredients from 12 fungicides and herbicides, each used at 5 mg/kg in the substrate. Active ingredients, including 2,4-D, bentazone, clopyralid, and pyraclostrobin, were neither detected in the fifth instar larvae nor the prepupae. This could be resulted from the excretion of these active ingredients by the BSFL (Gold et al., 2025). Other active ingredients were present below the permitted maximum residue levels on fruits and vegetables for human consumption (FAO, 2017). However, the composition of the substrate must still be monitored as higher levels of active ingredients might adversely affect the survival of BSFL and cause economic loss.

The mycotoxin content of FLW is also a safety concern for bioaccumulation in BSFL. Papin et al. (2026) analysed FLW such as wheat bran, carrot, apricot, and salads for common mycotoxins. Only zearalenone (0.01 to 0.02 mg/kg) and ergot alkaloids (0.03 to 0.04 mg/kg) were detected at concentrations above the limits of quantification. However, the BSFL did not accumulate ergot alkaloids and bioaccumulation did not occur even when 20 µg/kg of aflatoxin B1 was spiked in the substrate (Tao et al., 2025). This could be due to the ability of BSFL to metabolise these mycotoxins. For example, BSFL can metabolise aflatoxin B1 to relatively less toxic aflatoxicol and aflatoxin P1 with the help of the cytochrome P450 monooxygenases (Meijer et al., 2019). Unlike the conventional feed crops such as corn and soybean that accumulate mycotoxins, BSFL metabolically degrade them. This attenuates the risk of mycotoxin contamination and effectively recycles FLW into feed.

Finally, microplastics in FLW are another source of concern in BSFL. The BSFL ingest microplastics at early larval stages, especially smaller particles, which constituted around 75% of the ingested microplastics. This preference for smaller particle sizes at early larval stages could be due to their narrow mandibular spacing. However, the size and shape of these microplastics did not affect their growth. As suggested by Planche et al. (2025), a three-day fasting approach can help the BSFL remove more than 90% of microplastics from the gut since the microplastics are excreted during this process and do not stay in the intestinal lumen nor enter the tissues of BSFL. Yet, fasting could decrease BSFL biomass and extend the production cycle, causing increased facility overhead and environmental footprint. Hence, the economic and environmental trade-off of the three-day fasting period must be considered and analysed. Last but not least, bioaccumulation of contaminants from the substrate into BSFL can occur without physiological costs. This asymptomatic tolerance implies that the physical health markers of BSFL, such as body weight, are unreliable indicators of safety. Hence, substrate selection and monitoring is necessary. Additionally, a pre-harvest fasting period can facilitate the excretion of contaminants, and thus minimises their retention in BSFL (Planche et al., 2025; Spranghers et al., 2025).

Case 3: Transforming food loss and waste to single-cell proteins

The SCP are the third method for circularly redirecting FLW to the food system, using specific microbial strains for FLW fermentation. It addresses waste management, FLW mitigation, and demand for sustainable livestock protein (Alves et al., 2025). The microorganisms—non-pathogenic, non-toxic bacteria, microalgae, and fungi—utilize FLW and agri-food by-products as fermentation substrates. Some studies have found that a multi-complex substrate consisting of various FLW sources requires minimal processing to produce SCP (Aggelopoulos et al. 2014; Tropea et al., 2022). For instance, Tropea et al. (2022) studied the simultaneous biotransformation of multiple FLW, such as fish, pineapple, banana, apple, and citrus peels, by yeast (*Saccharomyces cerevisiae)*. This multi-complex substrate yielded 30% more protein after 144 hours of fermentation by the yeast compared to the initial protein content of the substrate. Aggelopoulos et al. (2014) also observed that yeast cultured on a multi-complex substrate including FLW such as orange peel, molasses and brewer's spent grains raised the CP content of the fermented substrate up to 38.5% w/w on a dry weight basis. The two studies highlight using mixed animal- and plant-derived FLW without separation for SCP production. This approach cuts FLW processing needs, transportation, and disposal costs, while yielding nutrient-complete feed from diverse sources.

Nutritional value of single-cell proteins

The SCP can be produced in large quantities owing to the rapid growth rate of microorganisms (Bratosin et al., 2021). The SCP are rich in nutrients, especially proteins, whose level depends on the microorganisms and substrates used. For instance, the CP level of SCP produced from *Aspergillus flavus* (NRRL 21882) was higher when using pea pods as substrate (61%), rather than using potato peels (51%) or banana peels (35%) (Khan et al., 2024). Similarly, yeast *Rhodotorula glutinis* cultured on molasses with yeast extract as the nitrogen source produced 18.6 g/L biomass after 5 days, with protein and lipid contents of 36.4% and 11.1%, respectively. Replacing yeast extract with corn steep liquor reduced biomass to 16.1 g/L and protein to 30.1%, while increasing lipid content to 13.9% (Li et al., 2025). The amino acid profile of SCP also varies depending on the microorganism and the source of carbon and nitrogen in the substrate (Bratosin et al., 2021). *Candida utilis* and *Komagataella pastoris* were studied and cultured on defatted soybean meal to produce SCP. The level of essential and limiting amino acids such as methionine and lysine were higher in SCP compared to defatted soybean meal alone (Anowar and Morais, 2025). Instead, other research reported a deficiency in sulphur-containing amino acids such as methionine and cysteine, especially in fungal SCP (Nasseri et al., 2011; Yuan et al., 2017). This could be due to the different substrates and the fungal species used. Despite this, deficient amino acids can be supplemented in the diet of livestock (Bratosin et al., 2021; Chalvon-Demersay et al., 2021).

Effects of single-cell proteins on livestock performance

With their high protein content, SCP have the potential to be included in the diet of a variety of livestock species, especially poultry. For instance, the soybean meal in the diets of Cobb-400 broilers was partially replaced by SCP up to 2% on a DM basis for 42 days, with no effect on final body weight. Conversely, when replacement was > 4%, the final body weight was significantly decreased by 7% and the breast percentage was significantly decreased by 3%. The blood biochemical characteristics such as haemoglobin, total protein, albumin, aspartate aminotransferase, and triglycerides, were decreased in groups with SCP inclusion > 2%. The serum level of uric acid remarkably increased up to 15% in groups with SCP inclusion > 4%, probably because of the increased level of nucleotides in SCP (Bhunia et al., 2023). A similar study on Cobb broilers using SCP (*Clostridium autoethanogenum*) suggested a 4% inclusion to replace soybean meal as beneficial (Wu et al., 2022). The SCP inclusion up to 4% did not affect the overall average daily feed intake, body weight gain, dressing percentage, thigh muscle and breast muscle yield, total cholesterol, total protein levels, and alpha diversity of gut microbiota but the *Firmicutes/Bacteroidetes* ratio in the finisher stage. This ratio was increased when SCP were added in the diets, which might be related to increased short-chain fatty acid production and better nutrient absorption (Wu et al., 2022). Other studies on chickens using SCP suggested inclusion levels ranging from 1 to 9% as safe and more than 10% as not recommended (Hombegowda et al., 2021; An et al., 2018; Asefa et al., 2001; El-Deek et al., 2009 and Pourelmi et al., 2018).

The SCP are also a good source of protein in pig feed. As indicated by Verstrepen et al. (2023), the SCP derived from yeast (*Cyberlindnera jadinii*) cultured on lignocellulosic substrate showed good digestibility of protein (41.4%) in an *in vitro* porcine gastrointestinal digestion model. The growth performance of weaned piglets was not affected when 40% of the CP were provided by SCP (*Candida utilis*) for 28 days (Cruz et al., 2019). The apparent total tract digestibility of the CP was increased by 2%, but the apparent ileal digestibility of CP as well as the trypsin activity and genes expression of nutrient transporters remained unaffected (Cruz et al., 2019). Both *in vitro* and *in vivo* studies suggested that SCP could be used in pig feed to partially substitute conventional protein and that the SCP can improve growth performance and nutrient digestibility in pigs under proper inclusion rate (Zhang et al. 2013; Bo et al., 2020). The limited inclusion rate for pig feed needs further investigation since this could be a bottleneck for large-scale SCP implementation in animal feed. The SCP can also serve as a protein source for ruminants. Inclusion of up to 6% SCP (Ajitein) in the diet did not affect the feed intake and growth performance of fat-tailed sheep (Ndaru et al., 2020). Supplementing 1% of a mixture of SCP, glycerol, and propylene glycol to Brazilian steers increased their daily weight gain by 1.23 kg/day and improved feed efficiency by 17%. The total weight gain also increased in supplemented steers (147.0 kg) relative to those not supplemented (124.5 kg; Gado et al., 2025), suggesting a growth-promoting benefit of SCP that in this case was added as a feed additive without aiming to replace conventional protein sources from the diet. A bacterial SCP (*Methylophilus methylotrophus*), Pruteen, was tested to replace soybean meal to meet 25% of dietary nitrogen requirements in dairy cows. The DM digestibility, intake of metabolizable energy, nitrogen balance of the animals and milk production remain unchanged with the inclusion of Pruteen (Teller and Godeau, 1986). When SCP were used to replace groundnut-cake as a protein source in lactating goats, increased milk production and palmitic acid content of milk fat were observed. However, the nutrient digestibility was lower in the SCP group (Mudgal et al., 1986). These studies suggested the possibilities of including SCP in the diet of ruminants but more studies on different aspects of SCP utilisation in ruminant nutrition are still warranted.

Safety concerns of feeding single-cell proteins to livestock

Stringent regulatory frameworks, safety assessments, and robust monitoring and testing protocols are instrumental in ensuring SCP safety. For livestock, SCP-based feeds must comply with feed regulations and meet nutrition requirements, without posing risks to animal welfare or to final consumers (Li et al., 2024). Li et al. (2024) reviewed the safety concerns in SCP. First, high nucleic acid levels in SCP can raise serum uric acid, potentially impairing kidney function and explaining poor livestock performance at high inclusion rates—thus requiring careful selection. Second, inefficient processing may leave active microbes, risking animal infections. Third, residual toxic metabolites like mycotoxins and cyanotoxins from microbes could harm animals if not fully removed. These safety concerns are bottlenecks for SCP large-scale implementation. However, if nucleic acid content poses a species-specific risk, the other two may be manageable through processing and monitoring.

Beyond safety concerns, other SCP production challenges persist. Fermentation demands equipment with automated controls for strict hygiene and conditions throughout the pipeline to prevent harmful microbes. Additionally, FLW substrates require pre-processing: as lignocellulosic material, they need size reduction and biochemical treatment to release fermentable sugars (Kumar et al., 2023). In summary, process costs, scalability, low inclusion rates, and production conditions remain bottlenecks for large-scale SCP implementation, though research and biotechnological innovations aim to address them (Li et al., 2024; Alves et al., 2025). Microbial SCP production offers environmental advantages as a reliable livestock protein source, producible year-round without seasonal or climatic limits. Circularity is achieved by using abundant, low-cost FLW as substrates, enabling replacement of conventional sources like soybean and fish meal to cut environmental impacts. Still, more studies are needed on livestock performance and safety.

Recommendations

This review examines three options to convert FLW into feed (Table S2). In order to optimise FLW utilization, an adaptation of the existing regulatory framework would be recommended. Combining the information addressed in this review, we proposed to classify FLW materials into three main categories: i) Category 1, unprocessed/minimally processed FLW, ii) Category 2, moderately industrial-processed FLW, and iii) Category 3, highly processed FLW. A further potential category could include FLW materials not eligible for livestock feeding due to safety or practical reasons. These materials can be used for industrial-related purposes, such as fuel conversion, composting, landfill, etc. This review focused on the first two categories because the third category has similarities with swill feeding and therefore presents regulatory limitations in several countries.

Category 1 FLW includes materials such as fruits, vegetables, and salads. These materials require minimal to no processing, are high in carbohydrates and low in DM content, making long-distance transport logistically and economically impractical. Consequently, Category 1 FLW is suitable for direct local livestock feeding. Examples include crop salads, ‘ugly’ fruits and vegetables, primarily for pigs and ruminants. For this FLW category, ensiling is an option to enable safe, long-term storage. Finally, FLW with low nutritional value can be used for insect or SCP farming, which subsequently become high protein and energy feed for aquaculture, poultry and pigs. Insects and SCP grown on FLW can also be marketed over long distances.

Category 2 FLW includes FFP and similar materials such as bakery leftovers. These materials require industrial-level moderate processing to become a feed ingredient. The processing stages involve unpacking, drying, and grinding, which requires energy input. In this context, it is necessary to limit the packaging residues and the presence of undesired compounds to maximum permitted levels. Accordingly, the use of this FLW should be based on traceability and feed inspection to verify compliance with regulatory limits. Category 2 FLW is high in carbohydrates and high in DM content, making it a calorie-dense feed ingredient with a long shelf-life. Consequently, long-distance transport is logistically and economically feasible. As such, Category 2 FLW is suitable as a marketable high-energy source for all livestock species, with different inclusion rates depending on the target species.

Category 3 FLW includes food waste that requires high processing. Japanese “Ecofeed” is an example of this category, where food waste is sterilised with thermal and pressure-based treatments or fermentation. Consequently, the process of converting this FLW to feed is energy-intensive. Due to the nature of the starting materials, it is necessary to monitor the efficacy of sanitisation to ensure feed safety. While Category 3 FLW is usually rich in nutrients, the low DM content and need for sanitisation make long-distance transport impractical. Moreover, legal regulations limit the use of these materials to a few countries. Therefore, Category 3 FLW is suitable for repurposing food waste into pig feed in areas that legally permit its use.

As seen above, categorisation of FLW is the foundation for the regulatory framework, providing guidelines to policy-makers, regulation authorities, feed manufacturers and farmers (Fig. 2). The regional nature of farming and the availability of specific FLW streams must be considered when formulating appropriate regulations. In addition, before *in vivo* validation, *in silico* transfer models (e.g. feedfoodtransfer.nl) can be used as a preliminary, species-specific screening tool to assess the optimal feed use of various FLW materials.

Conclusions

The circular utilisation of FLW as feed requires the interaction of food and feed systems to redirect nutrient leakage in FLW back to the food system in a circular way, according to the one-nutrition approach. The different pathways that livestock, insects, and SCP follow to upgrade FLW represent a resource for circularly recycling FLW in multiple ways. The options discussed in this review have inherent advantages and weaknesses, Hence, it is difficult to develop a single, universally applicable decision-making framework, as many factors influence the final decision, such as the FLW source, nutritional content, safety aspects, the processing rate required for feed conversion and the target animal species, the latter also linked to the inclusion rate of FLW in the diet. The systematic use of FLW as a feed is still far from being realized in some areas of the world. This is because several challenges remain, particularly the safety and affordability of FLW, along with its variable nutritional content, which depends on the type of FLW material and seasonality. These challenges lie in the context of restrictive regulations that reduce the possibility of widespread FLW use. To safely accelerate the adoption of FLW in feed, further research involving large-scale, long-term *in vivo* studies, along with life cycle and cost assessments are needed. Regional specificity of FLW production and use also needs to be considered to increase the reliability of FLW as a multi-level feed and potentially simplify current regulatory frameworks.

Ethics approval

Not applicable.

Data and model availability statement

None of the data were deposited in an official repository, but are available upon request.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors did not use any artificial intelligence assisted technologies in the writing process.

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Declaration of interest

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Tables

Table 1. Production efficiency trends in terrestrial livestock, aquaculture species, and insects, expressed as feed conversion rate (FCR; kg feed per kg of animal product). Sources: Pinotti et al. (2021b), Naylor et al. (2021), Van Raamsdonk et al. (2017).

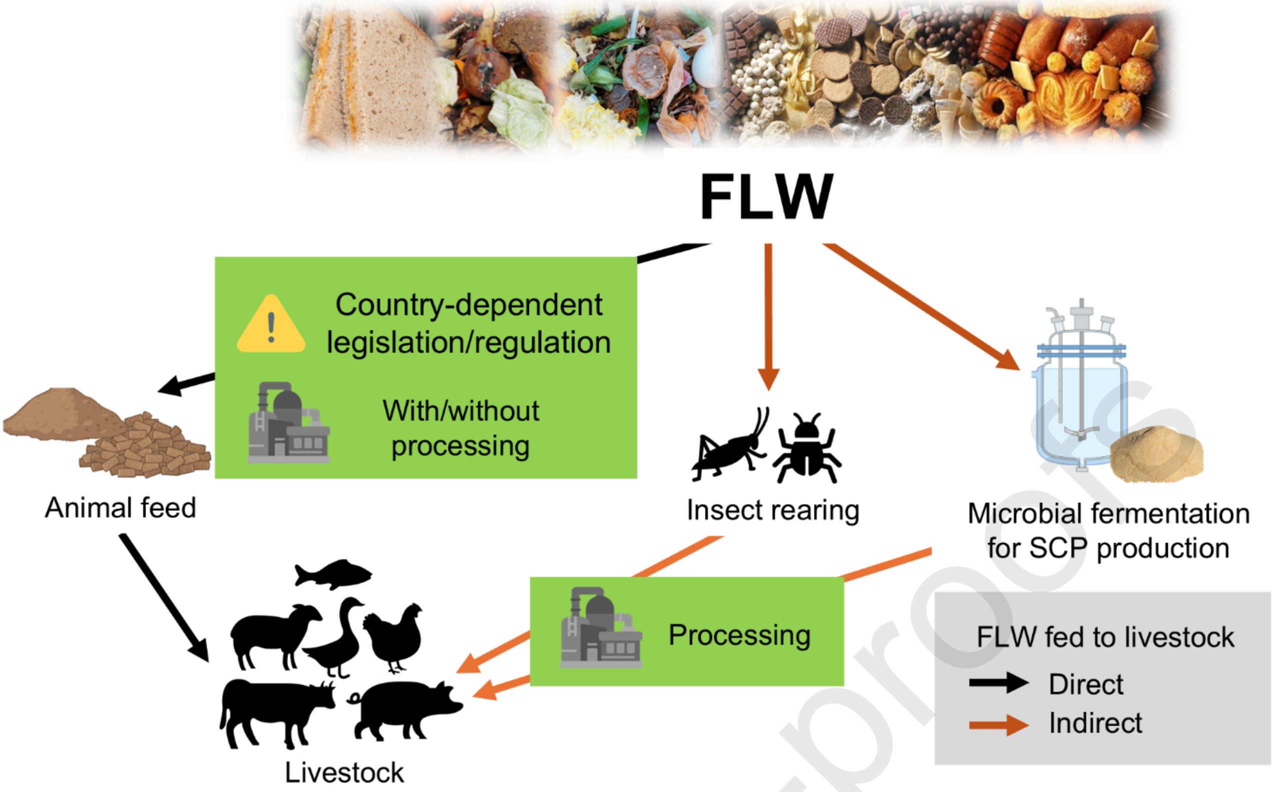
	FCR		
Items	20th century	Today	Efficiency improvement
Terrestrial products			
Poultry meat	4.5	1.9	57%
Turkey meat	6.0	2.5	58%
Eggs	4.3	2.1	51%
Milk	2.2	0.7	68%
Pork (100 kg)	4.3	2.7	37%
Beef (400 to 700 kg)	9.0	7.0	22%
Overall mean	5.05	2.81	49%
Aquaculture products			
Shrimp	2.0	1.6	20%
Salmon and trout	1.4	1.3	7.1%
Marine fish	2.0	1.7	15%
Chinese carp	2.0	1.7	15%

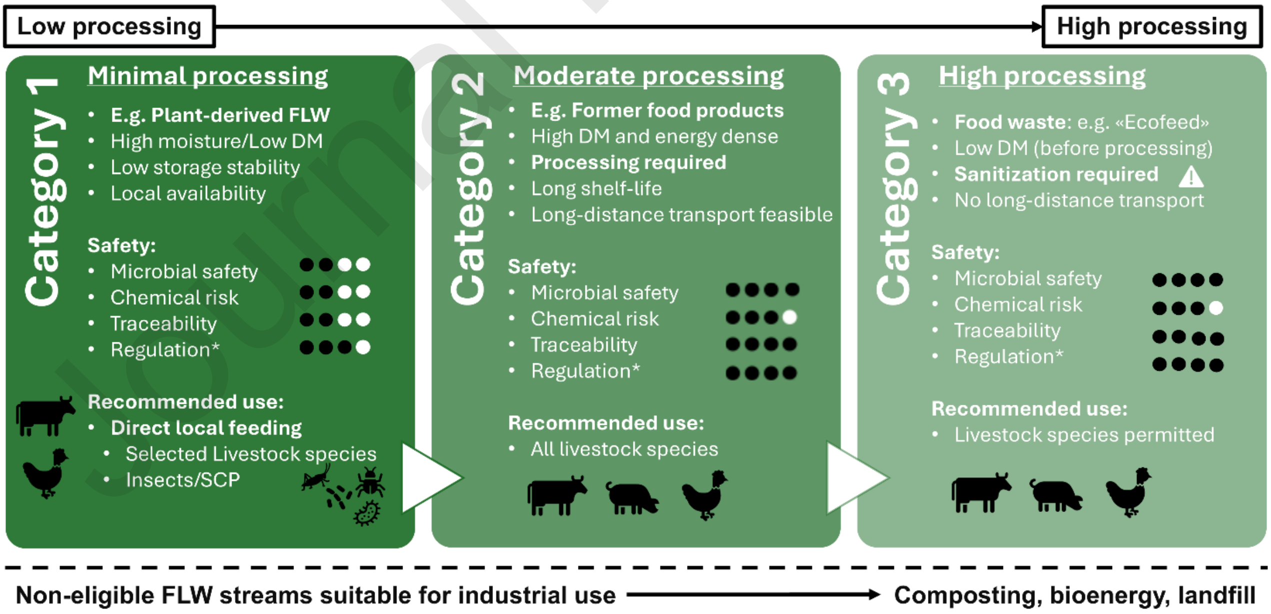
Tilapia	2.0	1.7	15%
Catfish	2.0	1.3	35%
Overall mean	1.9	1.55	18%
Insects			
Black soldier fly	-	1.4 to 2.6	-
Yellow mealworm	-	3.8 to 6.1	-
House cricket	-	1.3 to 10.0	-
Argentinean cockroach	-	1.5 to 2.7	-
Overall mean	-	3.68	-

Figure captions

Fig. 1. Schematic representation of the formation of loss and waste from the food system and how it is fed to livestock. Abbreviations: FLW = food loss and waste; SCP = single-cell proteins.

Fig. 2. Proposed categorization of FLW in relation to its use in livestock feeding systems. For the safety score, more filled circles indicate higher safety control and/or regulatory confidence. Abbreviations: FLW = food loss and waste; SCP = single-cell proteins. *Different in each country.


FLW
Country-dependent legislation/regulation
With/without processing
Animal feed
Insect rearing
Microbial fermentation for SCP production
Processing
Livestock
FLW fed to livestock
Direct
Indirect


Low processing
High processing
Category 1
Minimal processing
E.g. Plant-derived FLW
High moisture/Low DM
Low storage stability
Local availability
Safety:
Microbial safety ●●○○
Chemical risk ●●○○
Traceability ●●○○
Regulation* ●●●○
Recommended use:
Direct local feeding
Selected Livestock species
Insects/SCP
Category 2
Moderate processing
E.g. Former food products
High DM and energy dense
Processing required
Long shelf-life
Long-distance transport feasible
Safety:
Microbial safety ●●●●
Chemical risk ●●●○
Traceability ●●●●
Regulation* ●●●●
Recommended use:
All livestock species
Category 3
High processing
Food waste: e.g. «Ecofeed»
Low DM (before processing)
Sanitization required
No long-distance transport
Safety:
Microbial safety ●●●●
Chemical risk ●●●○
Traceability ●●●●
Regulation* ●●●●
Recommended use:
Livestock species permitted
Non-eligible FLW streams suitable for industrial use
Composting, bioenergy, landfill