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Review: Nutritional, safety, and environmental aspects of former foodstuff products in ruminant feeding ☆

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ABSTRACT

As a consequence of global population growth, rising incomes, urbanisation, and improved household economics, the demand for animal products is expected to increase. This has led to a heightened focus on the challenge of allocating natural resources between the production of human food and livestock feed. The livestock industry, particularly ruminant producers, is seeking cost-effective, human-inedible feed alternatives due to the rising costs of forage production and grains. Former foodstuff products (**FFPs**), derived from food industry leftovers (material remnants of food processing), represent a promising strategy for reducing feed–food competition, particularly through partial replacement of grains and concentrate feed in ruminant diets. FFPs are rich in simple sugars and fats; however, their excessive intake by ruminants may increase the risk of subacute rumen acidosis and modulate microbial protein synthesis and methane emissions. Furthermore, chemical substances present in FFPs (polyphenols and theobromine), packaging remnants, and microbiological contaminants may alter ruminal ecosystems and fermentation, methane emissions, milk quality, and animal health. This review summarises the nutritional composition of FFPs, with a focus on their potential to replace energy feeds, the risks and benefits of FFPs in ruminant nutrition, and legislation regarding the use of FFPs in livestock diets. It concludes by highlighting further research that could promote sustainable FFP practices.

Implications

To meet the increasing demand for animal-source food while respecting planetary boundaries, it is necessary to identify alternative feed sources. This review discusses the potential of former foodstuff products as alternative feed ingredients for ruminant nutrition. It examines the nutritional and chemical characteristics, safety concerns, and *in vitro* and *in vivo* evidence regarding former foodstuff products in ruminant diets, considering the benefits and risks associated with their use. The objective was to provide insights for all stakeholders involved in the food system to encourage a more efficient utilisation of former foodstuff products in ruminant diets.

Introduction

The growing human population has intensified pressure on global food systems, leading to increasing competition for natural resources, including arable land. A significant societal challenge arises from the fact that land traditionally used to grow food for human consumption is increasingly being repurposed for livestock feed production. This shift exacerbates feed-food competition, raising concerns about land-use efficiency and the sustainability of both food and livestock production systems (Halmemies-Beauchet-Filleau et al., 2018). The rising costs of feedstuffs, particularly protein- and energy-rich concentrates, such as cereals and oilseed meals, further exacerbate the feed–food competition. Although ruminants rely primarily on forages, such as corn silage, alfalfa, and grass hay—feed sources that are inedible to humans and can be grown on marginal lands—modern livestock systems often supplement these diets with concentrates that compete directly with human food production (Mottet et al., 2017).

According to the waste hierarchy framework of the circular economy, the most preferred food waste management strategies

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are, in order of priority, reduction, redistribution, animal feed, anaerobic digestion, composting, incineration, and landfilling (Parsa et al., 2023). Although using food loss and waste (**FLW**) as animal feed should not be the primary solution, it serves as a valuable opportunity to recover lost natural resources and reintegrate them into the food production system, thereby enhancing the circularity and sustainability of resource utilisation. This approach aligns well with the broader goal of transitioning to a circular economy in food production, which aims to improve resource efficiency through the formulation of livestock diets using cost-effective and preferably human-inedible ingredients.

The European Green Deal, including the Farm to Fork strategy, emphasises sustainable and closed-loop systems to lower waste and minimise greenhouse gas (**GHG**) emissions. In the European Union, dairy and meat sectors contribute approximately 15% to total GHG emissions (Hafner and Raimondi 2020; aan den Toorn et al., 2020). Ruminants play a key role in converting non-edible biomass into human-edible protein. However, their production is associated with significant emissions, particularly from enteric methane. Nutritional strategies such as supplementing fats, plant compounds, and optimising feed ratios have been investigated to mitigate these emissions (Grossi et al., 2019; Vaghar Seyedin et al., 2022; Manoni et al., 2023). Nonetheless, identifying alternative feed ingredients that do not compete with human food remains a major challenge (Muscat et al., 2020; Jalal et al., 2023). In this context, utilising former foodstuff products (**FFPs**) emerges as a promising solution to mitigate feed–food competition by promoting the use of non-edible biomass. While the primary goal of FFP use is to enhance resource efficiency and sustainability, a positive side effect is the potential reduction of emissions through better feed utilisation and less reliance on conventional feed sources. This approach contributes to a more sustainable food system by minimising waste, conserving natural resources, and reducing environmental footprints (Pinotti et al., 2023).

The FFPs, as defined by the European Union Catalogue of Feed Materials (Regulation (EU) No 2017/1017), are foodstuffs initially manufactured for human consumption but no longer suitable for the human market due to production errors, surplus production, or logistical challenges. This includes: (i) products with incorrect shape, colour, flavour, labelling, or packaging, which do not meet the commercial food standards; (ii) surpluses from discontinued food product lines; (iii) surpluses resulting from logistical challenges; (iv) unsold products after seasonal or sport events; and (v) products expired according to internal sell-by dates (Regulation (EU) No 2017/1017). Importantly, FFPs are distinct from household food waste or catering reflux and are regulated differently (Tretola et al., 2019; Luciano et al., 2020; Mazzoleni et al., 2023a). In addition, FFPs can be termed differently according to different authorities/countries, for instance, ex-food, bakery meal, or confectionery/bakery by–products (Pinotti et al., 2021). Despite their potential, incorporating FFPs into ruminant diets presents several challenges.

The nutritional composition of FFPs is highly variable and influenced by several factors, including the seasonality of food industry leftovers, the type of raw materials utilised, and the specific manufacturing processes involved. This inherent variability necessitates regular analysis and tailored formulation to ensure consistent feed quality and meet the dietary needs of livestock. However, experienced former foodstuff processors have developed methods to collect, analyse, and mix various food losses to produce a final commercial product with a chemical composition that is similar throughout the year (Tretola et al., 2019). Another concern is the chemical characteristics of FFPs, which are often rich in carbohydrates (Ottoboni et al., 2019) and fats (Giromini et al., 2017). High levels of simple sugars in FFPs, especially from confectionery products, can increase the risk of subacute rumen acidosis due to rapid fermentation in the rumen mainly by saccharolytic bacteria (Mullins et al., 2013). Additionally, the high–fat content in FFPs and the potential for spoilage and oxidation during processing and storage must be considered. Rancid fats may lead to the formation of oxidative by–products, such as aldehydes and ketones, which can be ecotoxic in the rumen, potentially lowering microbial protein synthesis and affecting methane production (Jenkins, 1993).

Former foodstuff products derived from cocoa, chocolate products, tea, or kola nuts typically contain theobromine and other ingredients rich in polyphenols, which may directly affect rumen/gut ecosystems, methane emissions, and milk production (Adamafio, 2013; Correddu et al., 2020; Rojo-Poveda et al., 2020). Since FFPs include a diverse range of food by–products, the presence and concentration of theobromine can vary depending on the specific composition of the feed material. In this regard, however, FFP processors must guarantee a theobromine content compliant with the law (Directive 2002/32/EC). FFPs originating from biomass commonly used in animal nutrition can also be a source of hydrolysable tannins, which, depending on the source and processing technique, can reduce rumen microbial activity, feed degradability, and total concentrations of volatile fatty acids (**VFAs**) produced (Correddu et al., 2020). Thus, although polyphenols in FFPs offer benefits, their negative properties must be carefully managed. Processing FFPs into feed ingredients involves sorting, unpacking, drying, grinding, and sieving. Despite efforts to remove packaging, the final product often contains small percentages of packaging particles, including microplastics (Mazzoleni et al., 2023b), posing potential risks to the environment as well as to human and animal health.

In summary, although FFPs offer a sustainable alternative to traditional feed ingredients and can help mitigate feed–food competition, their variable nutrient composition, potential chemical risks, and presence of packaging materials necessitate careful management and processing to ensure that they are safe and effective for animal nutrition. This review comprehensively examines the current state of knowledge on the nutritional and chemical characteristics of FFPs, delving into their potential risks when used in ruminant nutrition. Additionally, it scrutinises the current legislative framework governing their employment as animal feed. By exploring these aspects, this review highlights the nutritional benefits and chemical properties of FFPs and addresses the safety concerns associated with their use in ruminant nutrition. Moreover, it evaluates the environmental advantages that arise from incorporating FFPs into ruminant diets and presents a holistic view of their impact on agricultural practices. The analysis aims to provide valuable insights for policymakers, researchers, and farmers and to promote the sustainable and efficient use of these alternative feed ingredients in the livestock industry.

Production, processing, and safety of former foodstuff products

The European Union regulations and directives for food manufacturing processes and safety

Surplus food from manufacturers, distributors, and retailers is collected and sorted to exclude items unsuitable for feed (e.g., contaminated products or those with excessive packaging remnants). Depending on the region, this collection is either centralised—with specialised operators aggregating materials from multiple sources—or decentralised, where individual producers (such as bakeries) manage their own by–products and deliver them directly to farms. Since FFPs originate from surplus food materials, including products past their best-before dates, there is a potential risk of microbial contamination, spoilage, or degradation of certain nutrients. According to the European Former Foodstuff Association, the safety and hygienic quality of FFPs is guaranteed through HACCP management, full compliance of FFP processing plants to food safety regulations, advanced traceability, and rigorous storage rules (EFFPA, 2025a,b). Indeed, to mitigate these risks, proper handling and storage (typically up to 6 months, personal communication of M. Tretola, Agroscope) of FFPs is essential. To ensure safety and extend shelf life, FFPs undergo various processing methods, such as heat treatment, drying, milling, and pelleting. Heat treatment is applied to reduce microbial load and inactivate potential pathogens, and drying reduces moisture content to prevent spoilage. The dried product is then milled to create a consistent feed ingredient that can be stocked separately and mixed with other ingredients to produce a final compound feed. When different ingredients are mixed together, they are usually pelleted to ensure uniform nutrient distribution and facilitate the handling of the final product.

FFPs are valid feed alternatives defined by the European Commission and monitored by guidelines from the European Union Catalogue of Feed Materials (Reg. EU 2018/851, European Commission, 2018). FFPs have been shown to possess a low risk of spoilage and great microbiological quality. For instance, in FFPs, samples collected from FFP processing plants to be readily used as feedstuffs were found to be free of *Salmonella spp*. and with lower than threshold limits of *Enterobacteriaceae*, *Escherichia coli*, coagulase-positive *Staphylococci*, *Bacillus cereus* and its spores, *Clostridia*, several pathogenic bacteria yeast, and mould (Tretola et al., 2019). This aspect is of importance not only for farm animals but also for related personnel throughout the food chain and, eventually, consumers, as animal feed is a known contributor to the disease burden of humans through the food chain (Mahami et al., 2019). Other biological hazards that need to be considered are viruses, although currently, there is no primary literature investigating this aspect (James et al., 2022). Nevertheless, heat treatment is frequently applied in ultra-processed foods, which are the main ingredients comprising FFPs. Further heat processing, such as pelleting, is often used to manufacture FFPs into final feed products. These steps can increase the biological safety of FFPs (Van Raamsdonk et al., 2023). To our knowledge, no studies have specifically investigated the oxidation status of FFPs, leaving a gap in understanding their susceptibility to lipid oxidation and their potential impacts on feed quality.

Depending on the national context, members of the European Former Foodstuff Association are developing a feed hygiene management guide for the FFP processing sector to inform the sector's minimum requirements (EFFPA, 2025a,b). In Europe, FFPs are subject to several food safety regulations and directives. Specifically, FFPs must follow Regulation (EC) No 1837/2005 for feed hygiene, which also applies to all feed business operators. FFPs must follow Regulation (EC) No 178/2002—the General Principles and Requirements of Food Law, which states that producers of feed for food-producing animals are intrinsically part of the food chain. This implies that the feed must be safe and may not have any adverse effects on animal or human health (Article 15), the feed must be traceable and identifiable throughout the supply chain (Article 18), and actions are taken to withdraw unlawful products from the market (Article 20). FFP processors are also expected to adhere to Regulation (EC) No 767/2009, regarding the marketing and use of feed. This regulation stipulates the labelling requirements for feed. Given that FFPs may contain or may be derived from animal by–products such as milk, eggs, honey, and gelatine, they are identified as "category 3" animal by–products and are specifically described in Article 10(f) of Regulation (EC) No 1069/2009, the health rules regarding animal by–products and derived products not intended for human consumption. However, most of these problems and concerns do not exist for ruminants because their feed is regulated by the TSE regulation/prohibition that prevents the use of feed contaminated by animal by-products, including FFPs, for ruminants.

FFP processors are subjected to Regulation (EC) No 882/2004 on "Official controls performed to ensure the verification of compliance with feed and food law". With the aim of delivering safe feed to the market, FFP processors must comply with Directive 2002/32/EC on "undesirable substances in animal feed," which sets maximum limits for undesirable substances in animal feed. However, the legal status of former foodstuffs destined for animal feed has yet to be concretely defined in the European Union legislation. To emphasise that FFPs are not a 'waste' in legal terms, FFP processors follow Article 5 of the Waste Framework Directive 2008/98/EC) stipulating the criteria of by–products. Finally, the Commission Notice C/2018/2035 on the "guidelines for the feed use of food no longer intended for human consumption" includes very useful clarifications for the eligibility of FFPs that have fallen on the floor at the food factory level and the labelling of food expiration dates.

Physical and chemical hazards

Compared to biological hazards, concerns about the potential presence of physical hazards, namely, foreign object or packaging remnant contamination, in FFPs seem to be more relevant. Although processing steps such as grinding, drying, dissolving, sieving, wind shifting, and magnet or electric magnetic field application are routinely performed to remove packaging materials from collected FFPs, packaging remnant contamination may still occur after the post-treatment monitoring of unpacked FFPs (Mazzoleni et al., 2023b; Lin et al., 2024). In response to growing environmental concerns and the negative effects of traditional plastic packaging, a variety of approaches in the field of sustainable food packaging biomaterials are being considered. Examples include edible coatings and films made of biodegradable polymers (Al Mahmud et al., 2024). Plastics are still the most commonly used food packaging materials, followed by paper, cardboard, regenerated cellulose, and aluminum foil. In a study by Mazzoleni et al. (2023b), cellulose was the most abundant remnant found in FFP samples obtained from different international processors. Although ruminants can digest cellulose, additives in printing inks and softeners in regenerated cellulose could still represent a risk to animals (Van Raamsdonk et al., 2011).

Certainly, foreign objects or packaging remnants cannot be accepted as part of the feed (Reg. (EC) No. 767/2009, European Commission, 2009 and 2018). However, as removing all the physical contaminants in FFPs is nearly impossible and because such small numbers of packaging remnants should not cause severe health risks in animals or humans (Van Raamsdonk et al., 2011 and 2012), applying a zero-allowance standard to the packaging remnants present in FFPs would only impede the utilisation of FFPs in livestock diets (Lin et al., 2024). The Dutch monitoring programme for feed materials conducted in 2005–2010 collected and analysed 160 FFP samples for plastic packaging remnants (Van Raamsdonk et al., 2011). The reports showed that about 90% of the samples had a level of packaging remnants below the tolerance level of 0.15% determined by the Netherlands and German authorities (Van Raamsdonk et al., 2011). Accordingly, for packaging remnants present in FFPs, an allowance level from 0.125% w/w up to 0.2% w/w is generally accepted nowadays (Kamphues 2005; Van Raamsdonk et al. 2011).

In summary, evaluations of FFPs suggest that FFPs are safe feed ingredients, both microbiologically and physically, with respect to regulatory limits. However, the potential effects of these amounts of packaging remnants on ruminal fermentation, performance, and health warrant further investigation. A starting point is provided by the overview work of Eichinger et al. (2024) regarding the effect of microplastics on the gastrointestinal microbiomes of humans, mice, chickens, and aquatic animals, which can possibly be transferred to the ruminal microbiome (Eichinger et al., 2023).

Regarding the safe use of FFPs in livestock diets, besides the above-mentioned biological and physical aspects, caution must be exercised concerning the presence and content of certain undesirable compounds, such as the theobromine in cocoa/chocolate products in FFPs, which may have toxic or anti-nutritive effects on animals (Adamafio, 2013; Rojo-Poveda et al., 2020). Theobromine is an alkaloid with a slightly bitter taste, which likely leads to reduced diet palatability and reduced DM intake in animals (Renna et al., 2022). It is also suggested to be an anti-nutritional factor, lowering diet digestibility (Pinotti, 2023). In monogastric, theobromine has been reported to hamper growth and increase lethargy in pigs, as well as delay egg-laying in chickens (Oduro-Mensah et al., 2018). For ruminants, adverse effects include reduced reproductive performance and sperm quality observed in sheep fed 30% DM cocoa meal for 150 days (average daily theobromine ingestion of 105 mg/kg DM; Macedo et al., 2023), decreased milk yield, and physical signs related to hyperexcitability, such as sweating, elevated respiration, and heart rates in dairy cattle (15 mg/kg BW per day; European Food Safety Authority, 2008). Moreover, toxicity symptoms and adverse effects, such as disorders of the central nervous system, can occur in dairy cows when theobromine intake is around 700 mg/kg of feed material (Klein et al., 2021).

Due to the unfavourable effects mentioned above, the European Food Safety Authority stipulated regulations on the concentration of theobromine in animal feed. Particularly, on an as-fed basis (feed with moisture content of 12%), theobromine content should not exceed 300 mg/kg in complete feed materials, except those in complete diets for adult cattle, which are 700 mg/kg of feed materials (Directive 2002/32/EC of the European Parliament and of the Council of 7 May 2002, European Commission, 2002). FFP inclusion in animal diets is unlikely to lead to exceeding the thresholds for theobromine, considering the inclusion levels in the diet and the fact that not all food materials used to prepare FFPs are theobromine-containing foods. However, investigations of the effects of FFPs on the rumen environment and ruminant performance and health should consider not only the FFP nutrient composition, its inclusion level in the feed, and the resulting dietary effects but also the possible impact of certain undesirable compounds present in FFPs, such as packaging remnants and theobromine, on these characteristics.

Other chemical hazards in FFPs are heat-induced contaminants such as acrylamide and semicarbazide, embodying health concerns such as mutagenic, carcinogenic, and cytotoxic effects. The occurrence and levels of acrylamide are especially high in thermo-treated and carbohydrate-rich foods, such as potato chips, biscuits, bread, and bakery products (Capuano and Fogliano, 2011), and these foodstuffs are all major components in the recipe of FFPs. Accordingly, a report by the European Food Safety Agency (EFSA, 2009) listed the acrylamide levels in different food commodities that can be sources of FFPs. These levels, however, are generally very low and should not pose a high risk, except when treatments such as autoclaving or feed irradiation are adopted (Twaddle et al., 2004). The latter is not the case for feed fed to farmed ruminants. Semicarbazide is a by-product formed after the thermal decomposition of azodicarbonamide, a flour additive in bakery goods banned in the European Union, Australia, and Singapore (Ye et al., 2011). Azodicarbonamide is also used as a blowing agent in plastic food packaging, which may be decomposed and migrate into food in the form of semicarbazide (EFSA, 2003). However, the occurrence and levels of such heat-induced chemicals have not been monitored in complete FFPs. Moreover, it has to be noted that FFPs are a blend of various food products and that, to be ready as feed, they receive further heat treatments which may again trigger Maillard reaction and decompose azodicarbonamide. Thus, the actual amount and presence of these undesirable substances in the final FFPs as feed can be more complicated and are still unknown. Further research in this aspect is required even though using azodicarbonamide in bakery products is banned in the European Union.

Potential of former foodstuff products as animal feed and their use in animal feeding systems

To fully assess the potential of FFPs as animal feed, it is crucial to quantify the amount of food lost or wasted worldwide. However, estimating global FLW remains complex, as available figures typically encompass both losses occurring along the supply chain and waste at the consumer level. The lack of harmonised global estimates further complicates precise quantification. A recent comprehensive study on global FLW (Gatto and Chepeliev, 2024) underscores these challenges while providing valuable insights. According to the study, global FLW in 2014 was estimated at 1.92 gigatonnes, marking a 24.0% increase since 2004. The most significant relative rise occurred at the manufacturing stage (+26.8%), driven by the growing consumption of processed foods. Nonetheless, agricultural production, postharvest handling, and storage remained the dominant contributors, collectively generating 956 million tonnes of FLW—equivalent to 49.6% of the total. Plant-based FLWs, particularly from horticultural products, sugar beet, and sugarcane, exhibited the highest growth, highlighting opportunities for implementing circular practices within the food system. In terms of absolute volume, North America (mainly the United States), China, and India were the largest sources of FLW, accounting for 42.6% of the global total (Gatto and Chepeliev, 2024).

According to the European Former Foodstuff Association, around 5 million tonnes of FFPs are processed annually in the European Union (EFFPA, 2025a,b). At the same time, the global bakery meal market is estimated to grow by 3.6% in the period 2024–2034 (from approximately USD 898–1 255 millions) (Choudhury, 2024). As reported above for FLW, it is difficult to collect robust information on FFP volume availability; nevertheless, although the 5 million tonnes of FFPs processed still represent a limited percentage of FLW biomass available for processing, the growing value of the bakery meal global market indicates that FFP processing rates are growing.

Former foodstuff products are incorporated into diets for various animal species, with notable differences between monogastric and ruminant feeding systems. In monogastric species, such as pigs and poultry, FFPs are most commonly processed into standardised meals or pellets. This processing enables uniform mixing with other ingredients in compound feeds and ensures a consistent nutrient profile. Conversely, in ruminant diets, FFPs are typically included as part of the concentrate fraction (as an ingredient that can also be pelleted), which is then combined with forages to create a total mixed ration (**TMR**). In decentralised systems, however, some producers supply FFPs directly to farms as fresh or minimally processed feed, necessitating on-farm handling measures to maintain feed quality. By contrast, centralised systems generally employ rigorous quality control, traceability, and advanced processing technologies to standardise FFPs, reduce variability, and enhance safety, as described above.

Nutritional composition of former foodstuff products

The nutritional composition of FFPs is subject to alteration as a consequence of the processing reactions of the food of origin. Food processing may include reactions such as Maillard, oxidation, and enzymatic reactions, as well as physical processes (e.g., boiling and freezing). These reactions alter the physicochemical structure of food, may reduce the vitamin and mineral content, and form flavours, aromas, and even unwanted compounds, such as advanced glycation end products, during Maillard reactions (Nisar et al., 2023). However, the major nutritional components of FFPs are carbohydrates and fat, derived mainly from the industrial sector of processed and ultra-processed bakery and confectionery products. Table 1 compares the average nutritional composition of FFPs with that of the main cereals used in ruminant nutrition (i.e., maize, wheat, and barley). FFPs are rich in non-structural carbohydrates such as starch and simple sugars (e.g., glucose, fructose, sucrose, and lactose), providing a source of ready-to-use energy for the animal (Liu et al., 2018; Pinotti et al., 2023).

Starch is one of the major components of FFPs, but its quantity in FFPs is highly variable because it is related to the starch content of the food product of origin (Giromini et al., 2017). As reported in Table 1, starch in FFPs is lower than in all cereals considered, but it is characterised by higher digestibility because of the thermal and mechanical processes occurring for processed and ultra-processed foods. Thermal processing typically involves temperatures ranging from approximately 120 °C to 200 °C, depending on the food type and processing method. Processed foods typically undergo less intense treatments, such as drying, boiling, or moderate baking, with the goal of enhancing the preservation and improving the palatability of the food. Ultra-processed foods are subjected to more intense thermal and mechanical processing, such as extrusion, deep frying and high-temperature baking (often higher than 150–200 °C). At such temperatures, Maillard reactions are likely to occur, leading to the formation of advanced glycation end products. These reactions can affect the nutritional profile of the feed, potentially altering the digestibility of proteins and the availability of amino acids (Pinotti et al., 2021). Furthermore, these processes alter the physicochemical structure of starch in FFPs, making it more hydrolysable by enzymatic action in the gastrointestinal tract, and consequently more digestible (Tretola et al., 2019; Pinotti et al., 2023).

Specifically, the thermal processing of starch results in gelatinisation, an order-to-disorder transition characterised by water uptake and disruption of the semi-crystalline structure of starch granules, leaching of amylose, and dissociation of amylopectin double helix (Liu et al., 2022). Subsequently, the leached amylose can bind lipids and proteins, forming starch–lipid or starch–lipid–protein complexes (Nguyen et al., 2019; Liu et al., 2022). Following gelatinisation, the temperature declines, and retrogradation occurs through the re-crosslinking of amylose and amylopectin, as well as the formation of local crystallised sections. Retrogradation is typically associated with reduced quality in starchy foods, as the crystallised structure is not fully restored (Liu et al., 2022). However, it is also linked to enhanced starch digestibility due to the amorphous structure of starch, making it more susceptible to enzymatic hydrolysis (Wang et al., 2021). Giromini et al. (2017) reported that the *in vitro* digestibility of wheat was similar to the average digestibility of six different FFP samples consisting of confectionery, bakery and pastry products, wheat by–products, wheat flour, extruded and puffed rice cakes and/or extruded corn in various inclusion rates. However, Ottoboni et al. (2019) observed that the same six FFP samples showed a higher glycemic index (6.13–39.98 higher by percentage) than the control samples (maize and wheat). These results indicate that despite a similar NDF content, FFPs may have a higher digestibility than conventional cereals, not only due to the industrial processing to which they are subjected (which makes the starch highly digestible) but also due to the high levels of simple sugars. Even at a similar NDF level, different ingredients, especially fibres, can interact within the feed matrix, thus affecting the digestion pattern of the diet (Ottoboni et al., 2019). These two components (NDF and simple sugars) are of particular importance in ruminant diets, as they influence the composition of rumen microbiota, rumen fermentation processes, and consequently, nutrient availability in the small intestine (Niwińska, 2012; Dong et al., 2021; Pinotti et al., 2021). For this reason, these aspects will be further examined in Section 4.

The fat content is the most distinct nutritional difference between FFPs and cereals (Table 1). Indeed, FFPs contain approximately four times more ether extract than cereals. The industrial processing of bakery products and FFPs commonly involves the use of margarine, butter, and hydrogenated vegetable oils (Albuquerque et al., 2017). Thus, FFPs have a higher level of monounsaturated fatty acids and a lower level of polyunsaturated fatty acids compared to conventional cereals (Luciano et al., 2022). Furthermore, the n-6:n-3 ratio is higher in FFPs than in conventional cereals (Khiaosa-Ard et al., 2022; Luciano et al., 2022). Studies on sugary and salty bakery and chocolate snacks from Brazil (Dias et al., 2015) and Turkey (Omeroglu and Ozdal, 2020) have reported that palmitic acid (C16:0) is the predominant saturated fatty acid, while oleic acid (C18:1) is the predominant monounsaturated fatty acid. Palmitic acid and oleic acid, along with linoleic acid (C18:2 n6), were also the most abundant in a sample of bakery by–products included up to 30% in an experimental diet for dairy cows (Khiaosa-ard et al., 2022). The fatty acid composition of FFPs and dietary sources in feed in general is crucial to determining the quality of animal-source products, such as meat and milk from ruminants. Furthermore, FFPs have NDF and ADF contents that fall within the range reported for cereals, except for barley, which shows the highest NDF content among cereals. Similarly, the CP content of FFPs and cereals is similar; therefore, FFPs are not a valuable protein source (Table 1). To our knowledge, there are no detailed studies on the protein quality and essential amino acid profiles of FFPs. Despite their low potential as a protein source, it is important to highlight that FFPs are rich in carbohydrates, which represent an interesting energy source for rumen microorganisms. Typically, carbohydrates make up 70–80% of the dairy cow's diet. The energy derived from carbohydrate digestion in the rumen drives microbial protein synthesis and, thus, contributes to the animal's protein requirements (Gozho and Mutsvangwa, 2008).

In the broad categorisation of food losses, FFPs are classified based on the steps of the feed–food chain and the industrial processing they undergo. The food ingredients from which FFPs originate are present in varying ratios in the final product and are influenced by seasonal trends and market choices. Indeed, seasonal fluctuations in the availability and types of surplus ingredients can lead to considerable differences in macronutrient and micronutrient contents, making it challenging to standardise their nutritional profiles. However, when used as animal feed, FFPs must undergo appropriate processing procedures to guarantee a homogeneous feed ingredient that is suitable for incorporation into animal diets (Westendorf, 2000). Typically, FFP processors have stocks of FFPs comprising diverse food products already present in the processing facility. Thus, they can formulate and balance the nutritional composition of the final FFPs by using the storage of different types of FFPs, thereby minimising nutritional variability.

Furthermore, processed and ultra-processed foods that compose FFPs exhibit similar nutritional characteristics on a global scale, rendering them ready-to-eat and highly palatable. In a meta-analysis by Martini et al. (2021), high consumption of ultra-processed food by humans was positively correlated with increased intake of saturated fats and free sugars but negatively correlated with proteins, fibre, and micronutrients in different regions of the world. However, most FFPs still exhibit compositional variability, a concern that is also an intrinsic characteristic of cereals, as observed by the similar ranges of values reported in

Table 1
Average nutritional content of former foodstuff products (FFPs) and cereals used in ruminant nutrition. The values are presented as mean ± SD, and in brackets, min and max values are reported only for FFPs.

Item (g/100 g DM)	FFPs	Maize	Wheat	Barley
DM	90.4 ± 1.7 (87.7–92.1)	88.1 ± 3.1	89.4 ± 2.6	91.0 ± 3.5
EE	9.6 ± 1.8 (6.5–12.2)	4.2 ± 1.0	2.3 ± 1.1	2.2 ± 0.6
NDF	12.9 ± 5.4 (6.4–20.5)	9.5 ± 2.3	13.4 ± 6.2	20.8 ± 8.6
ADF	4.0 ± 2.6 (2.2–7.9)	3.4 ± 1.0	4.4 ± 3.6	7.2 ± 2.8
CP	11.2 ± 1.0 (10–12.9)	9.4 ± 1.3	14.2 ± 2.3	12.4 ± 2.1
Ash	2.9 ± 0.9 (2.1–4.9)	1.5 ± 0.5	2.0 ± 0.3	2.9 ± 0.8
Starch	47.7 ± 4.5 (42.3–53.4)	66.6 ± 6.4	61.6 ± 8.5	54.5 ± 6.3
Sugars	16.7 ± 5.6 (10.5–21.3)	–	–	–

Source: Data on FFPs from Humer et al. (2018a), Tretola et al. (2019), Luciano et al. (2020 and 2021), Pinotti et al. (2021), Grossi et al. (2022); data on cereals from NRC (2001); and data on cereal starch from Rodehutscord et al. (2016), Stein et al. (2016), and AFZ (2017). Abbreviation: EE = ether extract.

Table 1. The compositional variability of cereals is caused by multiple factors, that is, different cultivars, geographical origin, harvesting period of the year, environmental factors, and soil conditions (Rodehutscord et al., 2016). To investigate the compositional variability of FFPs, Liu et al. (2018) collected 46 different sources of bakery meal, named industrial bakery food leftovers and similar to FFPs, from commercial feed mills across the US and observed a low CV in the nutritional content. This indicates that the supply of multiple bakery meal sources from different geographical areas has a limited impact on the nutritional composition of the final products. Another study reported that the chemical composition of 11 sources of bakery meal showed some variability but generally complied with values reported in the literature (Stein et al., 2023). These findings support the broader application of FFPs in animal nutrition, as farmers and stakeholders do not need to rely only on single FFP processors located in specific areas, thereby reducing transportation costs and GHG emissions (Liu et al., 2018).

Former foodstuff products in ruminant feeding

The use of FFPs in ruminant nutrition has been less explored than in monogastric animals, particularly pigs. The omnivorous nature of pigs and the structure of their gastrointestinal tract render them more capable of converting low-fibre, high-starch, and high-lipid feed ingredients such as FFPs into energy (Pinotti et al., 2023). Additionally, pigs rely more on cereal-based diets than ruminants (Ganesan and Rajauria, 2020; Unlu, 2021). Thus, the introduction of FFPs into pig diets has been more expedited and established with greater success than in ruminant diets. This is due to the fact that a larger proportion of pigs' diet can be replaced by FFPs, reaching up to a 30% inclusion rate (Luciano et al., 2021; Mazzoleni et al., 2023a).

However, the use of cereals as an energy source for ruminants has become fundamental. During specific phases of the productive lifespan of ruminants, such as early to mid-lactation, high-starch cereals are preferred over dietary fibre both for meeting the high glucose requirement for milk production and providing rapidly fermentable starch and high energy levels, which support high productive yields (Deckardt et al., 2013; Allen, 2015; Humer and Zebeli, 2017). In addition to being reliable energy sources, FFPs are less-competing feedstuffs that can be employed to replace human-edible cereals in animal diets. This has the benefit of reducing competition between humans and animals for the same resources (i.e., cereals) while simultaneously enhancing the sustainability of the animal nutrition sector. However, the overall impact of FFPs on food and nutrition security also depends on their effects on animal production. In light of the existing *in vivo* feeding trials in the literature (Kaltenegger et al., 2020 and 2021; Grossi et al., 2022; Khiaosa-ard et al., 2022; Mammi et al., 2022; Neglia et al., 2023; Reiche et al., 2023, Table 2), which are discussed in more detail below, several assumptions can be made regarding the use of FFPs for ruminants.

First, FFPs can effectively replace conventional energy sources, such as cereal grains and concentrates, in the diet of lactating dairy cows, both during early lactation (33.2 days in milk (**DIM**) in Reiche et al., 2023) and during mid-lactation (149 DIM in Kaltenegger et al., 2020; Khiaosa-ard et al., 2022; 60–110 DIM in Mammi et al., 2022). The feeding trials involving FFPs ranged from 21–42 days. In other studies, FFPs were included in the diets of dairy lactating buffaloes (*Bubalus bubalis*) on 111 DIM for a period of 90 days (Neglia et al., 2023) or in the diets of fattening heifers for a longer period of 145 days (Grossi et al., 2022). On a DM basis, the inclusion rate of FFPs in the diets has been of 12.2% (Mammi et al., 2022), 15% (Neglia et al., 2023), 16.7% (Reiche et al., 2023), 22.8% (Grossi et al., 2022), and up to 30% (Kaltenegger et al., 2020; Khiaosa-ard et al., 2022). In most cases, FFPs were delivered in TMRs, replacing dietary energy sources such as corn and soybean meal (Grossi et al., 2022) or wheat and triticale (Kaltenegger et al., 2020; Khiaosa-ard et al., 2022).

Second, due to their high fat and simple sugar content and low starch and NDF and ADF levels compared to traditional feed ingredients, FFPs may influence the energy metabolism of ruminants (Kaltenegger et al., 2020; Grossi et al., 2022; Khiaosa-ard et al., 2022). Indeed, it has been suggested that the increase in sugar content from 4.5% to roughly 6% in the FFP diets might have increased lipogenic factors, as it is known that the fermentation of sucrose in the rumen leads to lipogenic precursors, such as acetate and butyrate reducing propionate (Oba and Allen, 2003; Kaltenegger et al., 2020). This latter decreases the content of glucogenic precursors in FFP diets (Kaltenegger et al., 2020; Khiaosa-ard et al., 2022). Kaltenegger et al. (2020) further observed that increasing dietary FFP inclusion altered the fat:starch ratio in FFP-containing diets, thus leading to an increased DM intake in FFP-fed cows.

Third, although FFP diets have a lower starch content, the presence of heat-processed starch in their ingredients may enhance starch digestibility, providing the animal with a source of rapidly digestible starch and energy, as well as a potential rapid accumulation of short-chain fatty acids, which may result in a reduction in rumen pH (Darwin et al., 2018). The impact of the use of FFPs in ruminant diets, particularly with respect to nutrient composition and possible contaminants present in FFPs on ruminant performance and health, is detailed in the following section.

Rumen environment

Higher concentrations of non-structured carbohydrates, especially processed starch and simple sugars, as well as fats, alongside reduced levels of dietary fibre and protein could have several effects on ruminants *in vitro* and *in vivo*. Humer et al. (2018a) compared different isonitrogenous but not isoenergetic diets contain-

Table 2
Summary of the main dietary effects of former foodstuff products (FFPs) on ruminant performance, milk quality, health, rumen ecosystems, and diet digestibility.

Item	Animals	Control diet	Duration	Type of FFPs	FFP inclusion (on DM)	Main findings (comparing FFPs to control groups)	References
in vitro							
	Rusitec trial (rumen fluid collected from 3 non-lactating Holstein cows)	Meadow hay and concentrates (42–58 ratio)	3 runs (10 d/run)	Bakery by-products (BBPs)	15, 30 and 45% to replace wheat and rye	● Reduced pH (FFPs 45%) ● Decreased ammonia concentration (30 and 45% FFPs) ● Decreased methane production (FFPs 45%) ● Higher ruminal degradation of starch and lower degradation of CP and fibre ● Reduced bacterial diversity (FFPs 45%) and modulation of bacterial community (reduced abundance of fibrolytic bacteria *Butyrivibrio;* increased abundance of *Prevotella, Roseburia,* and *Megasphaera)*	Humer et al. (2018a)
	In vitro fermentation trial (rumen fluid collected from 4 adult Italian Mediterranean Buffalo cows)	Fresh sorghum and concentrates (62–38 ratio)	120 h	Biscuit meal	40% to replace flaked corn	● Unaltered pH ● Comparable fermentation kinetics between the control and FFP diets ● Similar organic matter degradability ● Low gas production and VFA rates but comparable between control and FFPs diet	Neglia et al. (2023)
in vivo							
	24 Lactating Simmental cows ● DIM: 149 ± 22.3 d (mid-lactation) ● Parity: 2.63 ± 1.38 ● Initial BW: 756 ± 89.6 kg ● Initial ECM: 29.6 ± 0.3 kg/d ● ECM: 29.4 vs 31.5 vs 34.3 kg/d (control vs 15 vs 30% FFPs)	Grass and corn silage and concentrates (50–50 ratio)	35 d	BBPs	15 or 30% to replace wheat and triticale	● Increased ATTD of all nutrients except non-fibrous carbohydrates ● Increased digestible organic matter intake ● Decreased fecal pH but increased total fecal VFA concentration and proportion of fecal butyrate, indicating increased hindgut fermentation ● Decreased cellulolytic bacteria and increased amylolytic bacteria in faeces ● Decreased richness and diversity indices of the fecal microbiota, inferring risk of hindgut dysbiosis ● Increased total DM intake and milk yield ● Similar BW changes, feed efficiency, and energy balance ● No differences in milk constituents except lower milk urea nitrogen and lower milk protein yield ● Higher mean reticular pH but less time when reticular pH was below 5.8 and lower subacute rumen acidosis index pH 5.8 ● Decreased blood glucose and insulin concentrations but elevated non-esterified fatty acids, β-hydroxybutyrate, and cholesterol concentrations ● Similar daily total eating, drinking, chewing time, and overall ruminating time	Kaltenegger et al. (2020 and 2021)
	408 Limousine beef heifers ● Fattening period ● Initial average BW: 338 ± 24 kg ● Average daily gain: 1.02 vs 0.99 kg/d (control and FFPs)	Wheat, corn and soybean meal	145 d	Biscuit (bakery former foodstuffs, BFFs)	22.8% to replace corn and soybean meal	● Similar ATTD of all nutrients except for higher sugar and pectin ATTD ● Similar BW, average daily gain, feed intake, and feed conversion ratio, indicating the great palatability of the FFP diet ● Maintained health condition and similar incidence of acidosis ● Similar carcass characteristics ● Improved production-related environmental parameters	Grossi et al. (2022)
	24 Simmental cows ● DIM: 149 ± 22.3 d (mid-lactation) ● Parity: 2.63 ± 1.38 ● Initial BW: 756 ± 89.6 kg ● Initial ECM: 30 ± 0.3 kg/d ● ECM: 29.4 vs 31.5 vs 34.3 kg/d (control vs 15 vs 30% FFPs)	Grass and corn silage and concentrates (50–50 ratio)	21 d	BBPs	15 or 30% to replace wheat and triticale	● Increased total fatty acid intake ● Similar proportions of linoleic acid and α-linolenic acid and n6:n3 ratio but increased proportion of conjugated linoleic acid in milk fat	Khiaosa-Ard et al. (2022)
	8 Holstein cows ● DIM: between 60 and 110 d ● Parity: 1.63 ± 0.64 d ● Initial average BW: 588 ± 50 kg ● Initial milk yield: 40.7 ± 3.9 kg/d	Alfa-alfa and grass hay and concentrates (42–58 ratio)	21 d	BFFs	12.2% to replace starch and protein sources (grain mix and mixed flakes)	● Similar BW, DM intake, water intake, and daily rumination time ● Similar daily average reticular pH but longer time when pH below 5.8 ● Similar milk constituents ● Similar fecal composition and total tract fibre digestibility	Mammi et al. (2022)

(continued on next page)

Table 2 (*continued*)

Item	Animals	Control diet	Duration	Type of FFPs	FFP inclusion (on DM)	Main findings (comparing FFPs to control groups)	References
	● ECM: 34.9 vs 35.6 kg/d (control vs FFPs)						
	50 Italian Mediterranean buffaloes ● DIM: 111 ± 3.63 d ● Age: 4.6 ± 0.3 years ● Parity: 2.9 ± 0.2 ● Average BW: 676 ± 16 kg ● Initial milk yield: 11.7 ± 0.7 kg/d ● ECM: 15.8 ± 0.5 vs 15.6 ± 0.6 kg/d (control vs FFPs)	Fresh sorghum and concentrates (62–38 ratio)	90 d	Biscuit meal	40% to replace flaked corn	● Similar feed intake and body condition score ● Similar milk yield, milk constituents, and milk fatty acid composition, except higher proportions of trans fatty acids and stearic acid in milk fat	Neglia et al. (2023)
	17 Holstein and Red Holstein cows ● DIM: 33.2 ± 0.4 d (early lactation)	Fresh herbage and concentrates	42 d	BBPs	16.7% to replace concentrates	● Increased water-soluble carbohydrate intake but decreased starch intake ● Decreased milk lactose ● Larger range of reticular pH throughout the trial	Reiche et al. (2023)

Abbreviations: ECM = energy–corrected milk; ATTD = apparent total tract digestibility; DIM = days in milk; VFA = volatile fatty acid.

ing 42% meadow hay and 58% concentrate. The control concentrate contained 45% wheat grain and 13% rye per DM. In the FFP-containing concentrates, 30 or 45% DM of wheat grain were replaced by 30 or 45% DM FFPs. The inclusion of 30 or 45% FFPs in the diet showed several effects on the ruminal ecosystem *in vitro* (Humer et al., 2018a). Specifically, Humer et al. (2018a) observed a 23 and 33% decrease in ammonia concentration in ruminal fluid due to the inclusion of 30 and 45% FFPs, respectively. This can be explained by a decrease in protein degradability and increased energy availability for microbial protein synthesis, aligning with the observed decrease in the isobutyrate proportion, an end product of ruminal deamination of dietary amino acids (Wallace, 1994).

Furthermore, the inclusion of 45% FFPs resulted in a 9.54% reduction in daily methane production (Humer et al., 2018a). This reduction is likely due to the lower NDF and ADF content in FFPs and the higher fat and oil concentration compared to cereal grains. Fibre serves as the primary substrate for methane production by ruminal microbes (Hammond et al., 2016). These nutritional differences resulted in a shift in ruminal microbiota *in vitro,* with a reduction in fibrolytic bacteria, such as *Butyrivibrio* and *Anaerostipes* (Humer et al., 2018a). The decrease in these organisms has previously led to an observed decrease in the acetate proportion of rumen liquid (Esquivel-Elizondo et al., 2017). By contrast, *Prevotella, Roseburia, Megasphaera*, and *Acidaminococcus* increased in abundance due to FFP inclusion (Humer et al., 2018a). These observations are associated with the observed increase in propionate and isovalerate formation (Humer et al., 2018a). The increased abundance of *Prevotella* may explain the increased proportion of propionate in the FFP group, as this genus produces propionate (Mickdam et al., 2017). *Megasphaera,* a major fermenter of soluble sugar (Pitta et al., 2014), can convert lactic acid to acetate and propionate (Henning et al., 2010). Furthermore, a significant reduction in ruminal pH was observed *in vitro* with the inclusion of 45% FFPs (pH 6.59) but not with 30% FFPs (pH 6.60), compared to the control (pH 6.63) (Humer et al., 2018a).

Regarding *in vivo* experiments, Kaltenegger et al. (2020) and Kaltenegger et al. (2021) conducted a trial with 24 Simmental dairy cows. The cows were fed a TMR based on grass and corn silage along with concentrates. In this study, grain-based concentrates (CP: 681 g/kg DM) were replaced with FFPs at either 15% (CP: 686 g/kg on DM) or 30% of feed DM (CP: 725 g/kg DM), resulting in increased concentrations of sugar and fat. The difference in energy content between the different concentrates was not specified in the study. In contrast to the *in vitro* observations, the authors observed that FFPs elevated ruminal pH and reduced the risk of subacute rumen acidosis by lowering the time for the pH under 5.8 (−15%) compared to control cows. According to the authors, higher ruminal pH in cows fed FFPs may be related to the effects of FFPs on the development of rumen papillae and their capacity to uptake short−chain fatty acids produced in the rumen during the fermentation of starchy grains. However, this study provided no information about the effect of FFPs on the VFA, methane production, or rumen microbial community, but the authors observed a decrease in cellulolytic phyla *Fibrobacteres* and an increase in amylolytic phyla, such as *Proteobacteria* in the faeces. This can be explained by the elevated sugar (up to 6% of DM in the FFPs diet vs 4.5% in the control diet) and fat content (up to 4% of DM in the FFPs diet vs 2.4% in the control diet) resulting from FFP inclusion.

Mammi et al. (2022) found no significant differences in daily average ruminal pH and VFA or ammonia concentrations between Holstein dairy cows fed a corn-based concentrate (133 g CP/d; 1.58 Mcal/g DM) and cows fed a concentrate with corn replaced by 25, 50, 75, or 100% DM FFPs (138–147 g CP/d; 1.73–1.70 Mcal/g DM). Similarly, in the experiment by Reiche et al. (2023), no differences in daily average ruminal pH were observed in Holstein dairy cows fed herbage and a concentrate that included 55% FFPs (112 g CP/kg DM; 8.8 MJ/kg DM) as replacement for cereals compared to cows fed the cereal-based control concentrate (i.e., about 16.7% on total diet DM; 104 g CP/kg DM; 8.5 MJ/kg DM).

It appears that FFPs have more pronounced effects on the ruminal ecosystem and fermentation *in vitro* than *in vivo*, but this observation needs to be further validated due to the very limited number of currently published experiments with relatively small numbers of animals. However, this aspect could still be valid, since other *in vitro* studies on sugar fermentation showed changes in ruminal VFA production and a decrease in ruminal pH, which was not consistently confirmed under *in vivo* conditions (Oba, 2011). By contrast, many *in vivo* studies have reported that feeding sugars does not decrease the overall daily rumen pH (Kaltenegger et al., 2020 and 2021; Mammi et al., 2022). This has been observed also on other types of diets, such as when sugar-rich diets based on fresh or ensiled sugar beets have replaced starch-rich diets based on maize silage in dairy cow nutrition (Olijhoek et al. 2023). Experimental diets with sugar beets were much higher in total sugars (132, 178, and 80 g/kg DM for fresh, ensiled with additives, and without additive sugar beets, respectively) than the control diet (42 g/kg DM). Assuming that how the feed is provided and the availability of dietary sugars both contribute to modulating rumen pH and VFA production, no variation in rumen pH and total VFA (expressed as mmol/L) was observed between the experimental diets and the control (Olijhoek et al., 2023). One explanation for this observation could be the continuous removal of VFA from the system, which occurs only *in vivo* through the absorption of VFA across the rumen wall (Oba et al., 2015). This process is facilitated by the possible activities of Na^+/H^+ exchangers, which appear to be increased due to the higher abundance of sugars compared to the higher abundance of starch in the rumen, thereby allowing for increased VFA absorption through simple diffusion across the rumen wall (Graham et al., 2007; Etschmann et al., 2009; Connor et al., 2010). Therefore, researchers have suggested that heightened Na^+/H^+ exchanger activity represents an adaptation to the enhanced sugar fermentation occurring in the rumen, helping to regulate acidity and pH to some extent (Oba et al., 2015).

Ruminant performance and product quality

Beyond the effects of FFPs on the rumen environment, some studies have investigated their effects on ruminant performance and health, although there are variations in results across the studies. Kaltenegger et al. (2020) and Kaltenegger et al. (2021) demonstrated that lactating Simmental cows (149 ± 22.3 DIM) fed concentrates containing 30% FFPs without grains had 7% higher DM intake and produced 12% more milk per day (35.1 kg/d) compared to the control cows (30.6 kg/d) fed concentrate without FFPs but with 30% grains, presumably due to the altered fat-to-starch ratio and elevated energy availability of the FFP diets (Kaltenegger et al., 2020). Evidence indicates that elevated fat and lower grain can reduce the hypophagic effects of propionate by reducing its flux to the liver, thus elevating feed intake in dairy cows (Allen, 2000). Furthermore, the milk fat content tended to increase in the study, which could be related to the increased ruminal pH and the higher availability of acetate and butyrate as precursors for *de novo* fatty acid synthesis (Kaltenegger et al., 2020). Additionally, it is known that a decreased ruminal pH is often associated with lower milk fat-to-protein ratio (Danscher et al., 2015; Humer et al., 2018b). Similar effects on milk composition were observed by Khiaosa-ard et al. (2022) in Simmental dairy cows fed 30% FFPs compared to control cows (149 ± 22.3 DIM). FFP-fed cows secreted more milk fatty acids (expressed as kg/day) and exhibited a shift in the fatty acid profile, with a higher proportion of conjugated linoleic acid and C18:1 fatty acid, while C16:0 fatty acid tended to decrease, likely due to the specific fatty acid composition in the FFP (Khiaosa-ard et al., 2022). However, no increase in the percentage of polyunsaturated fatty acids in total milk fatty acids was observed, despite the higher intake of these fatty acids through FFPs, suggesting that ruminal lipolysis and biohydrogenation still occurred (Khiaosa-ard et al., 2022).

However, the results from other studies showed inconsistencies. In Mammi et al.'s (2022) study, milk yield tended to be higher, and milk protein was significantly higher in cows fed FFPs compared to the control cows, whereas no significant differences were observed in other milk quality parameters. Neglia et al. (2023) investigated TMRs in buffaloes fed either with green forage (fresh sorghum) or FFPs and observed no differences in milk yield, quality, or feed intake between the two groups. However, increased trans fatty acids and stearic acid were detected in the milk of buffaloes fed FFPs compared to the green forage group, presumably due to the higher proportion of partially hydrogenated oils in FFPs (Neglia et al., 2023). The longer ruminal transit time in buffaloes, which optimises fibre fermentation and VFA production (Infascelli et al., 1995), may explain the differences in biohydrogenation patterns between buffaloes and dairy cows. These findings highlight the need for further research to determine how differences in diet composition, ruminal microbiota activity, and species-specific digestive physiology influence the effects of FFPs on ruminant performance and health. Future research should focus on long-term feeding trials and the mechanisms underlying variations in milk composition and ruminal metabolism.

Environmental implications of former foodstuff products as feed

Nowadays, more than 30% of concentrate feed commodities are consumed by ruminants (Chang et al., 2019). Even though ruminants are not the main consumers of cereal grains compared to monogastric, such feed commodities are commonly provided to cattle in a feedlot. Furthermore, compared to 2010, the global demand for meat and milk is estimated to grow by 73 and 58%, respectively, within 30 years due to population and income growth as well as increasing middle–class formation and urbanisation (Gerber et al., 2013). This implies that the number of livestock raised is likely to increase.

Primarily, ruminants are reared on permanent or temporary grass that account for a quarter of the Earth's land mass (FAO, 2023). However, owing to the ongoing "livestock revolution," industrial and intensive production systems have also been actively introduced in ruminant farming. This will bring about greater amounts of primary crops required to be processed and used as concentrate feed (Govoni et al., 2023). In fact, 40% of all arable land is used for feed crop cultivation, including energy sources, such as cereals and tubers, and protein sources, such as oilseeds and pulses (Mottet et al., 2017). Additionally, a third of total agricultural water use is dedicated to livestock production, and 98% of such use produces feed ingredients (Mekonnen and Hoekstra, 2012). Meeting the growing demand for animal products while guarding planetary boundaries is challenging (Beal et al., 2023), but actions and initiatives have to be taken to address this issue.

At a global level, food waste and loss lead to the wastage of 30% of agricultural land, 20% of freshwater consumption, and 38% of total energy consumption, and generate 8–10% of anthropogenic GHG emissions (FAO, 2019; IPCC, 2019). Instead of discarding food losses such as FFPs, redirecting them as part of livestock diets can be beneficial. Theoretically, the use of FFPs in ruminant nutrition could mitigate the current pressure to utilise finite natural resources and environmental impacts arising from feed crops and livestock production. However, to date, studies assessing environmental indicators regarding the substitution of conventional feedstuffs by FFPs in ruminant diets are scarce. Grossi et al. (2022) demonstrated that the substitution of corn and soybean with FFPs and wheat wet distiller's grains on beef cattle in intensive production led to a reduction of GHG emissions (−1.00 kg CO_2 eq of GHG), water, and land use for feed production (−72.38 L and −1.20 m^2), and human-edible resource consumption (0.95 kg) per kg of cold carcass weight. Hence, the improved sustainability indicators should be attributed to both FFPs and wheat wet distiller's grains, leaving the independent effects of FFPs on environmental impact mitigation unclear. Hansen's (2024) study of data from two previous feeding trials (Guiroy et al., 2000; Dvorak et al., 2001) with modelling approaches suggested that compared to a traditional corn-based diet, feeding growing-finishing steers FFPs, respectively, at 40 and 55% DM in the diets led to a 45–63% reduction in land use (ha/animal) for feed production, a 37–61% reduction in water use intensity (L/kg live weight), a 14–19% reduction in GHG emission intensity (kg CO_2 eq/hd), and a 1–4% decrease in NH_3 emission intensity (kg NH_3/animal). Furthermore, diverting FFPs from landfills to growing-finishing steer's diets in feedlots resulted in 24–53% lower GHG emissions associated with FFPs from production to waste management. Importantly, when assessing the environmental footprint metrics of FFPs in ruminant nutrition, system boundaries and scenario-specific model coefficients are prerequisites. This may, in turn, create variations in the final estimates.

Certainly, the evidence obtained from studies in which FFPs were included in ruminant diets (Kaltenegger et al., 2020 and 2021; Grossi et al., 2022; Khiaosa-ard et al., 2022; Mammi et al., 2022; Neglia et al., 2023; Reiche et al., 2023; Hansen, 2024) has increased responses on animal performance, productive yields, welfare, and environmental indications. Furthermore, if FFPs can be collected and processed into feed sources at the local level, the need for importation and transportation of feedstuffs could be reduced, which would be helpful in lowering the GHG emissions generated from feed trade and transport. In this manner, FFPs could be kept in the food chain, which complies with the goal of developing a circular economy, ameliorating environmental consequences, and enhancing resilience in the ruminant production system.

Conclusion

According to available *in vitro* and *in vivo* studies on the inclusion of FFPs in ruminant feeding, FFPs seem to maintain adequate rumen function and pH, as well as good ruminant performance and health. Using FFPs as alternative energy sources to replace conventional materials such as cereal grains, fats, and oils, or molasses for lactating dairy cows and fattening cattle could potentially address the current feed–food competition without negative impacts on animal productivity or general welfare. Nevertheless, the objective can only be achieved when the chemical composition and inclusion rate of FFPs are meticulously regulated and harmonised with other feed ingredients. This is because the nutritional composition of the final diet is the determining factor influencing rumen microbial communities and the resulting animal performance, health conditions, and related products. To date, a limited number of studies have been published on this topic, and the results reported in *in vitro* and *in vivo* works are variable. Therefore, further validation is required to establish the safe use of FFPs in ruminant diets from a nutritional point of view. Furthermore, there is a lack of data concerning the effect of undesirable substances potentially present in FFPs, including theobromine, packaging remnants, and associated chemicals on those packaging particles, on ruminal fermentation, as well as on ruminant performance and health. Information regarding environmental indicators in ruminants fed FFPs-included diets also requires further investigation using modelling approaches. In light of these considerations, the valorisation of food losses, such as FFPs, in ruminant nutrition is anticipated to become a more prevalent practice within the agri-food chain.

Supplementary material

Supplementary Material for this article (https://doi.org/10.1016/j.animal.2025.101512) can be found at the foot of the online page, in the Appendix section.

Ethics approval

Not applicable.

Data and model availability statement

None of the data were deposited in an official repository but are available upon request. A graphical abstract is available as Supplementary Material S1, providing a visual summary of the key findings and concepts presented in the study.

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

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None. We affirm no affiliations or interests that could improperly influence our work or the content of this paper.

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