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Review: Pig-based bioconversion: the use of former food products to keep nutrients in the food chain

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ABSTRACT

The primary challenge of agriculture and livestock production is to face the growing competition between food, feed, fibre, and fuel, converting them from resource-intensive to resource-efficient. A circular economy approach, using agricultural by-products/co-products, in the livestock production system would allow to reduce, reuse, and redistribute the resources. Former food products (**FFPs**), also named ex-foods, could represent a valid option in strengthening resilience in animal nutrition. FFPs have a promising potential to be included regularly in animal diets due to their nutritive value, although their potential in animal nutrition remains understudied. A thorough investigation of the compositional and dietary features, thus, is essential to provide new and fundamental insights to effectively reuse FFPs as upgraded products for swine nutrition. Safety aspects, such as the microbial load or the presence of packaging remnants, should be considered with caution. Here, with a holistic approach, we review several aspects of FFPs and their use as feed ingredients: the nutritional and functional evaluation, the impact of the inclusion of FFPs in pigs' diet on growth performance and welfare, and further aspects related to safety and sustainability of FFPs.

Implications

Livestock production is currently facing food insecurity, climate change, and increased land and water scarcity. Consequently, alternative feed ingredients are required, such as former food products, characterised by a high potential for enhancing livestock production sustainability. Former food products allow to upgrade food surplus to feed ingredients and reduce food losses in the agri-food chain. Pigs are ideal for converting former food products and other by-products unsuitable for human consumption into high-quality animal proteins due to their intrinsic nature as omnivores and the nutritional profile of former food products.

Introduction

Livestock production must conciliate animal productivity and welfare, feed safety, environment, and production costs. The efficiency of animal feeding is crucial for livestock production, since it represents up to 65–85% of the farm gate value of poultry and pigs (Luciano et al., 2020). The production of feed relies on natural resources that could be used for other purposes, such as food, fuel, and fibre production, thus exacerbating the so-called 4-F competition (feed, food, fuel, and fibre). Further, the growing demand for natural resources needed for energy production requires sustainable solutions to improve the land and water use (Govoni et al., 2021 and 2022). For instance, water-saving strategies are waste reduction, dietary shifts, crop redistribution, as well as crop and water management (Govoni et al., 2021; Pinotti et al., 2021).

Owing to the high environmental impact, the livestock sector must reduce its reliance on natural resources related to the amount of animal product, expressed as footprint/product ratio (e.g., water, mineral, and land footprint) (Flachowsky and Meyer, 2015; Govoni et al., 2021 and 2022). Indeed, animal production generates a high environmental footprint. Although animals can convert different types of plant biomass (from grass for ruminants to cereals in the case of poultry and pigs) into high-quality animal proteins, this conversion leads to the loss of a certain amount of energy and proteins (van Hal et al., 2019). For instance, around 32% of the global grain yield is used for animal feeding, and this percentage is doubled in developing countries (Pinotti et al., 2021). Given the growth

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of world population, it is necessary to find innovative and more sustainable feed ingredients because feeding livestock with grain might not be sustainable in the long term (van Zanten et al., 2015).

The great amount of food waste has raised the awareness of recycling/reusing it as a feed ingredient (Food and Agriculture Organization (FAO) and World Health Organization (WHO), 2019). Accordingly, the food recovery hierarchy is a valid solution to decrease the environmental footprint of animal production (Mourad, 2016). A starting point is the conversion of food losses into feed ingredients, which indicates the potential use of former food products (**FFPs**) as novel sources of feed materials (James et al., 2022). The major benefit of converting food losses into feed ingredients is to keep nutrients, micronutrients, and minerals in the food chain.

The introduction of FFPs in animal production will help redistributing resources between feed/food and energy sector. This paper provides a holistic discussion of FFPs on multiple aspects of their validity as innovative and sustainable feed ingredients. In particular, we review the existing knowledge about FFPs, how they are classified by European regulation, some aspects related to their nutritional composition as well as their safety. We also provide information on the life cycle assessment (**LCA**) of FFPs.

Food losses, food waste, ex-food or former food products

Food losses, food waste and FFPs are all terms referred to food efflux. Food losses are related to a decreased quantity or quality of food coming from the first part of the food supply chain, i.e., collection, storage, and transport (Fig. 1), thus leading to a reduced amount of food suitable for human consumption. In some cases, farmers do not harvest as the transport and labour costs are higher than the market price of the products or the market demand is not high enough. Packaging is another factor that can increase food losses. Indeed, a large amount of food is discarded because it does not meet the aesthetic standards of the companies and/or the size of the packages does not meet the expectations of the general public. Food waste refers to the material remaining after or produced during the processing, preparation, or sale as human food. This material is intended for human consumption, coming from any step of the food chain. Examples are restaurant, retail, and household food scraps. To distinguish between food losses and food waste, the former is usually related to post-harvest activities lacking infrastructural capacities, whereas the second typically comes from the later stages of the food supply chain (Fig. 1, Gustafsson et al., 2013). Undoubtedly, food waste is associated to human eating habits (Gustafsson et al., 2013). Based on the discussion above, the use of FFPs in animal nutrition is different from swill feeding (i.e., feeding food scraps/food waste to animals), which is not allowed in many countries (EU, US, Australia, etc.). The use of FFPs as feed ingredients could increase the sustainability of feed and food production, whereas swill feeding could post the risks of disease transmission from farm animals to humans (Dame-Korevaar et al., 2021).

The FFPs are food biomass destined for human consumption but no longer suitable to be placed on the market due to practical or logistical reasons, such as manufacturing and packaging errors (Fig. 2). The FFPs do not present any risk when used as feed ingredients since they are merely food that did not reach the human food market due to the defects described above (Pinotti et al., 2021). The European Former Foodstuff Processors Association (EFFPA) estimates that approximately 5 000 000 tonnes of FFPs are produced annually in the EU, thus indicating the high availability of this biomass for the feed sector (EFFPA, 2022). An estimated amount of 350 000–400 000 hectares of wheat can be saved by replacing it with 3 500 000 tonnes of FFPs as feed (Mottet et al., 2017). Nevertheless, only 3% of such biomass is currently reused as feedstuffs (Luciano et al., 2020).

Nutrient composition of former food products

Principally, FFPs can be divided into two distinct categories: leftovers derived from the confectionery industry (such as chocolates, biscuits, and sweet snacks) and leftovers derived from the bakery industry (such as bread, pasta, salty snacks, and potato chips), and/or high-quality baked products. The FFPs are generally rich in carbohydrates, in particular starch and simple sugars. Depending on where they come from, FFPs can also be rich in fats (Luciano et al., 2020). The average starch content of FFPs reaches levels of 50–60% on DM basis (Giromini et al., 2017). The average 10% protein content of FFPs does not lead them to be recognised as a good protein source for livestock (Luciano et al., 2020). Moreover, FFPs are a mixture of different types and sources of ex-foods, which makes a standardisation of their nutritional composition not easily achievable. This is in line with our studies where 60 different FFPs samples were analysed (Giromini et al., 2017; Luciano et al., 2020; Ottoboni et al., 2019). A great variability in the nutritional composition of FFPs, especially for ether extract, crude fibre, ADF, and ash, was observed and is shown in Table 1. However, it should be noted that the data reported above represent only certain types of FFPs on the feed market.

Despite this, FFPs can still be considered an energy source with high nutritional value (a "fat-fortified version of common cereal

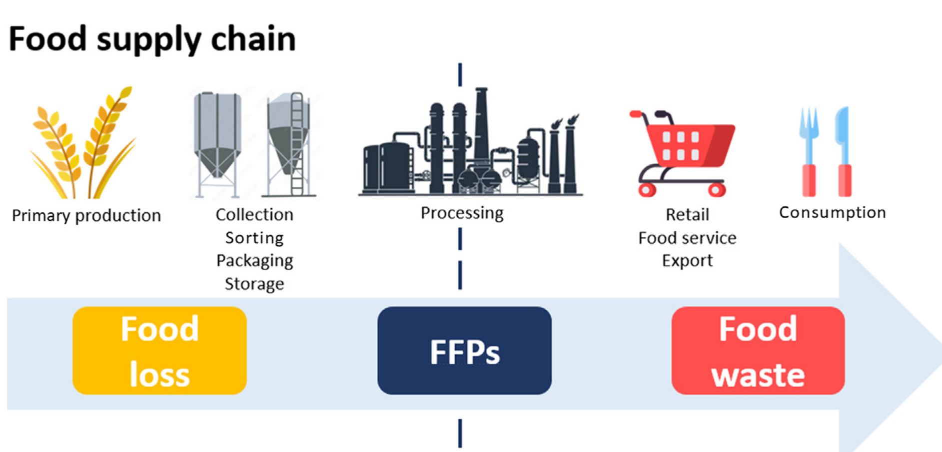

Fig. 1. How former food products (FFPs) fit into the food supply chain to be potentially used as feed ingredients for pigs and post-weaning piglets.

Fig. 2. Examples of unpackaged former food products (FFPs) ready to be processed into feed ingredients for the diet of pigs and post-weaning piglets.

Table 1
Average nutritional value of 60 samples of former food products (FFPs) used for the inclusion in the diet of pigs and post-weaning piglets.

Items (g/kg DM)	Mean	Min	Max
CP	11.1	2.1	16.7
EE	8.0	0.3	15.0
CF	2.8	0.5	13.4
NDF	17.1	2.1	50.5
ADF	5.8	0.4	22.1
Ash	4.1	0.7	8.6
NSC	65.0	50.6	79.3
Starch	46.9	24.0	86.3
NFE	70.1	60.8	79.0
ME (MJ/kg DM)	15.4	11.4	19.0

Source: Pinotti et al. (2021).
Abbreviations: FFPs = former food products; EEs = ether extracts; CF = crude fibre; NSCs = non-structural carbohydrates; NFEs = nitrogen-free extractives; ME = metabolisable energy; min = minimum value; max = maximum value.

grains"), suitable for feeding growing animals. Generally, these ex-foods undergo various reprocessing procedures (mechanical and/or heat treatments), thus giving FFPs higher nutrient availability and altered digestive kinetics. To elucidate, industrial cooking can modify the chemical and physical characteristics of food (Klopfenstein, 1980), thus affecting the macro- and micro-nutrient bio-accessibility and bio-availability (Pinotti et al., 2021). Additionally, these processes affect the nutritional properties, in particular through the protein denaturation and the altered digestibility of the starch fraction (Giuberti et al., 2012). Indeed, the heat treatment on FFPs could result in starch gelatinisation, damaged starch structure, reduced lipid oxidation due to enzyme inactivation, increased soluble fibre content, together with a reduction in thermolabile vitamins and/or microbial load (Klopfenstein, 1980).

Regarding the chemical composition of FFPs, the contents of simple/free sugars and starch are of focus because they affect not only the kinetics of carbohydrate digestion, but also the potential glycemic index (**GI**; Ottoboni et al., 2019), which explains how quickly carbohydrate-containing foods can release glucose in the post-prandial bloodstream (Giuberti et al., 2012). FFPs are often heat-treated and therefore tend to have a higher digestibility than common cereals used in animal nutrition, since processed starch can modulate its digestion kinetics (Ottoboni et al., 2019) and the GI (Giuberti et al., 2012). Among the FFPs analysed in Ottoboni et al. (2019), a higher hydrolysis index (**HI**) and predicted GI were observed compared to unprocessed corn. Therefore, FFPs are a source of highly digestible carbohydrates and "ready-to-use" energy. These two elements must be considered when FFPs are included in complete diets, since they might alter the digestibility rate of the whole diet (Ottoboni et al., 2019).

Use of former food products in animal nutrition

According to some studies (Ottoboni et al., 2019; Tretola et al., 2019a; Luciano et al., 2020; Pinotti et al., 2021), it is possible to partially replace classic energy sources (cereal grains such as corn) with a balanced amount of FFPs in the diet of post-weaning piglets, without causing any changes in the chemical composition of the diet. It was observed that the growth performance of post-weaning piglets fed diets with a 30% FFPs replacement and of those fed a standard diet were comparable (Pinotti et al., 2021). In addition, the results showed that both *in vitro* and *in vivo* digestibility were higher in diets with 30% FFPs inclusion than in control diets. There were two major differences between the study conducted by Luciano et al. (2021) and Tretola et al. (2019b). First, the duration of the *in vivo* trial was 42 and 16 days, respectively. Second, the types of FFPs formulated in the experimental diets were sweet and salty FFPs separately and a mixture of both, respectively. However, in both studies, the inclusion level was the same (30%) and the experimental diets containing FFPs were formulated to be iso-energetic and iso-nitrogenous. In both studies, several indexes related to the growth performance of pigs such as average daily gain (**ADG**), feed intake (**FI**), and feed efficiency were not affected by integrating FFPs in the diets. Luciano et al. (2021) also reported that replacing 30% of standard ingredients with either sweet or salty FFPs did not affect the apparent total tract digestibility. However, a more recent study (Luciano et al., 2022) suggested that a complete substitution of corn with bakery meal (other names for FFPs) in the diet of newly weaned pigs could compromise the growth if the total inclusion level exceeds 30% DM. That is, during the five-week nursery period, increasing concentrations of bakery meal to replace corn tended to reduce ADG and gain-to-feed ratio of pigs (Luciano et al., 2022). The decline in growth performance may be dictated by the nature of the FFPs themselves. The high content of simple sugars in FFPs could raise the risk of osmotic diarrhoea in pigs as when the capacity of intestine is overwhelmed, the absorption of sugars is incomplete (Marks, 2013). Hence, depending on the inclusion level and the amount of free sugar ingested, FFPs might negatively affect the nutrient absorption in pigs.

To the best of our knowledge, no studies investigated the effects of FFPs inclusion in pig's diet on feed palatability. It has been hypothesised that pigs offered sweetened feeds start eating sooner after weaning and reduce the number of visits to the feeder (Sterk et al., 2008). Therefore, taste modifiers are regularly added to the feed to improve palatability and FI for weaned piglets. Our group recently performed a trial in pigs from post-weaning to finishing period fed a diet in which 30% of cereals were replaced by sugary or salty FFPs. The feeding behaviour of these pigs was also monitored. We observed that in the growing phase, pigs fed sugary FFP-based diet significantly increased the number of feeder visits per meal compared to those fed salty FFPs and standard diets. However, the FI per day and the FI per visit were similar among groups (Authors' personal communication).

Besides growth performance and palatability, the evaluation of general welfare and gastrointestinal health of pigs is also indispensable when discussing the impacts of FFP-included diets. Concerns regarding the use of FFPs on gut health arise from the processed or ultra-processed nature of these ingredients. Starch gelatinisation or protein denaturation can increase the digestibility of FFPs. Hence, the high digestibility and the high simple sugar content of FFPs compared to the unprocessed cereals commonly used in pig nutrition could affect the structure and biodiversity of the host gut flora. This would lead to a reduced amount of undigested nutrients reaching the large intestine, which are available for microbial fermentation in the hindgut (Pinotti et al., 2021). Eventually, possible consequences on commensal species could lead to an overgrowth of harmful bacteria that induce oxidative stress-associated pathways in enterocytes, which will increase the production of reactive oxidative species and damage the intestinal epithelium (Gresse et al., 2017). Such risks are especially high in weaned piglets because of the weaning stress. Stressors such as the sudden change of diet and the isolation from the sows could create microbial dysbiosis in the piglets. A pilot study conducted by our research group showed that within 16 days after weaning, FFP diets reduced the richness and uniformity of the intestinal flora but had slight effects on taxa composition in pigs (Tretola et al., 2019a). A second study tested the effects of the FFPs throughout a longer period (42 days), from post-weaning until the end of the growing period (Tretola et al., 2022). When considering a longer period, FFPs had no effects on the abundance and biodiversity indexes of the microbial community. Only a few taxa, mainly the *Akkermansia* genus that is generally attributed to a healthy gut, increased with the partial replacement of traditional ingredients by FFPs (Tretola et al., 2022). These studies suggest that a 30% level of inclusion can be considered suitable for weaners, values in accordance with the European Food Safety Authority (EFSA) that reported that FFPs can only be fed to animals when combined with other conventional feed ingredients or with additives as FFPs alone do not provide the full nutritional requirements for the animals (James et al., 2022).

In conclusion, FFPs can be considered a valid source of simple sugar, processed starch, fat, and ready-to-use energy for the diet of post-weaning piglets. However, the level of inclusion in the diets must be carefully considered. For grower and finisher pigs, further studies are needed to understand whether a greater FFP inclusion level will affect their growth performance and meat quality.

Safety issues

The FFPs, unlike standard feed ingredients, are typically subjected to mechanical and heat treatment (Luciano et al., 2020). Safety aspects and the possible standardisation of the nutritional qualities of these products are requirements to be monitored and continuously improved (Amato et al., 2017; Tretola et al., 2017a; 2017b; Calvini et al., 2020). With regard to safety, the main issues are bacterial contamination and possible packaging residues. Undoubtedly, feed ingredients containing such residues are prohibited in the markets and the bacterial load must be below the levels established by the law to ensure animal well-being and health (Pinotti et al., 2021). Several microorganisms (bacteria, mould, and yeasts) are present in FFPs. The main hazard is pathogenic organisms such as *Salmonella* spp., although none of the FFP samples analysed in our previous studies had a detectable *Salmonella* ssp. load (Tretola et al., 2017a; 2017b). It is possible that the drying and cooking processes on FFPs allow the prevention of microbiological issues. In the same studies, microbiological load under safety levels was also confirmed for other species of bacteria through a total viable count (**TVC**). The values for TVC were found to be below 5 log colony-forming unit per gram (CFU/g) for all the FFP samples tested. This indicated high safety standards for bacterial contamination, as a TVC value of 6 log CFU/g is the threshold limit of spoilage. The authors reported values below the limit of detection ($\leq$2 log CFU/g) for *E. coli*, and *Staphylococci* and *B. cereus* showed very low values ($\leq$3 log CFU/g). The stability of these materials was also confirmed by small amounts of yeasts and moulds, which are the most critical organisms for the safety of FFPs used as feed ingredients (Tretola et al., 2017a; 2017b).

Another safety issue for FFPs is the possible presence of animal by-products. Indeed, FFPs containing products of animal origin must meet the requirements of Commission Regulation (EC) No 1069/2009 as well as other products of animal origin. This means that, in accordance with Commission Regulation (EC) No 999/2001, FFPs derived or containing milk products, egg products, and non-ruminant gelatine are the only products that may be used in feed for ruminant and non-ruminant farmed animals.

However, currently, there are no applicable analytical methods already published in literature and validated for the species-specific detection and quantification of animal protein in FFPs (Lecrenier et al., 2021). The FAO also highlighted that there is currently no inventory in which the most prominent and relevant hazards of FFPs are reported. Moreover, the presence and effects of chemical compounds deriving from packaging materials need to be monitored in relation to the final animal product (FAO and WHO, 2019). Plastic is the major component of packaging remnants, whereas paper, cellulose, and aluminium can be present to a lesser extent (Luciano et al., 2020; Mazzoleni et al., 2023). Regarding feed, a tolerance level of remnants was set at 0.125% w/w (van Raamsdonk et al., 2011). Our previous studies stated that, using different detection techniques, the same result was obtained: all the FFP samples evaluated were below the levels of tolerance. As a result, FFPs comply with feed regulation and are safe from potential remnant contamination (Tretola et al., 2019c; Luciano et al., 2022; Mazzoleni et al., 2023).

Sustainability issues and solutions

Agriculture, and livestock sector in particular, has become resource-intensive with a negative impact on the environment. Indeed, the growing global population and the higher incomes in developing countries are two key factors driving the increase in the demand for animal-source food in the last decades, in particularly the monogastric sector (Mottet et al., 2017). For instance, Govoni et al. (2022) estimated that pig meat production alone requires more than 455 000 000 tonnes of feed (concentrates such as grains and soybean, excluding co- and by-products), of which 70% are produced on arable land, thus creating competition of available land and water with food production. The current structure is that more than 40% of all arable land and more than 30% of cereal crop production are used for animal feeds, and approximately 23% of all captured fish are mainly destined for fish and livestock feed production (Sandströmet al., 2022). In this scenario, the circular economy and the 3R principles (reduce, reuse, recycle) offer many opportunities to become more resource-efficient. Large amount of crop residues and agricultural by-products such as brans, dried distillers' grains, and molasses could thus be used efficiently to support the growth of the livestock sector.

One option could be the use of co-products that can no longer be eaten by humans as livestock feed (Pinotti et al., 2020, Govoni et al., 2021 and 2022). Food could be provided globally by implementing a hypothetical scenario with no food-competing feedstuffs in animal diets, replaced by grass (for ruminants) and by-products (for monogastric). This strategy potentially implies a reduction in concentrate feed demand that could lead to savings of up to 26 and 21% of harvested land and freshwater use for feed, respectively, by 2050 (Schader et al., 2015). However, the use of grassland-based systems and the use of by-products as animal feed could also lead to reduced livestock efficiency and productivity. Crop residues are generally fibrous ingredients, so characterised by low digestibility and also poor protein quality, that could lead to reduced animal productivity (Sandströmet al., 2022). Consequently, other innovative and alternative feed ingredients are needed, such as FFPs (Luciano et al., 2020; Pinotti et al., 2021).

Food waste represents 23% of arable land, 24% of water used for crop production, and around 625 kcal/cap per day of food, including high amounts of macronutrients and micronutrients (Spiker et al., 2017). However, the reduced environmental impact due to the reuse of by-products (and so a reduced use of natural resources for agricultural purposes) needs to be deeply studied by integrating the concepts of water, mineral, and land (arable or total land) footprints (Govoni et al., 2021 and 2022; Pinotti et al., 2021). So far, several studies have considered the impact of different alternative feed ingredients when used as feed ingredients (Kavanagh et al., 2021; Pinotti et al., 2019; Rakita et al., 2021; Van Raamsdonk et al., 2023) mainly based on the nutritional quality of these by-products. From this perspective, the inclusion of energy-rich FFPs in livestock up to 30% does not affect animals' efficiency and productivity in post-weaning piglets (Luciano et al., 2020). Based on environmental impact perspective, the improvement in the efficiency of land and water use, achievable with the use of FFPs, may vary across countries and regions, with crop yields and climate being the main factors affecting this resource use efficiency. However, no studies discussed the environmental impact of the circular use of FFPs as feed ingredients. Instead, the impact of other by-products has been discussed.

Of note are the results obtained from a study based on the use of soy molasses as a by-product in animal nutrition (Sandströmet al., 2022). Considering the different by-products available (crop residues, by-products such as cereal bran and distiller's grains, livestock by-products from non-ruminant origins, and fisheries and aquaculture processing by-products) and the potential for substitution according to the nutritional requirements of livestock, the study highlighted how up to 72 000 000–103 000 000 tonnes of cereals, up to 3 800 000–6 000 000 tonnes of vegetable oils from oilseeds, 8 000 000–19 000 000 tonnes of pulses, and 2 900 000–3 900 000 tonnes of fishmeal (corresponding to more than 17 000 000 tonnes of whole fish) could be saved and directed for direct human consumption (Sandström et al., 2022).

The improvement in the efficiency of land and water use may vary across countries and regions. For instance, the reuse of FFPs in the livestock sector could also lead to land and water savings in distant areas of the world if the current international trade networks would be directed from a more efficient to a less efficient country in terms of crop production and/or FFPs processing could contribute to global land or water savings if trade is directed from a relatively more efficient to a less efficient country in crop production (Govoni et al., 2021 and 2022). Improving the sustainability of food-producing animal production, however, entails calculating both the current use of natural resources and identifying the local and downstream effects that such resource depletion is having on society and the environment. Another important aspect related to the sustainable potential of FFPs is their price. A competitive price would naturally increase the intention of replacing traditional ingredients with FFPs, which will consequently increase the sustainability of pork production. To our knowledge, there are no studies focusing on such aspects related to FFPs. A life cycle cost (**LCC**) analysis would clarify the cost-efficiency of the conversion of food leftovers into FFPs, for both the livestock producers and former foodstuff processors.

The LCA considers the entire life cycle of a product to obtain the impact categories to compare different scenarios, for example, in the case of animal nutrition, different feeding strategies (van Hal et al., 2019). So far, only a few studies have performed LCA to assess at what extent food waste, FFPs in particular, used as feed ingredients could mitigate the environmental footprint of livestock production. Using food waste as pig feed would save 1 800 000 ha of agricultural land, i.e., a 21.5% reduction in the current land use for EU pork production (Ermgassen et al., 2016). This involves replacing the 8 800 000 tonnes of grains currently used in pig diets, which is the equivalent of 70 300 000 tonnes currently consumed annually in Europe (Ermgassen et al., 2016). Compared to conventional diets containing grains, FFPs led to a reduction in numerous LCA impact categories such as natural land transformation, urban and agricultural land occupation, marine eutrophication, as well as freshwater and terrestrial ecotoxicity (Pinotti et al., 2021). Another study by Vandermeersch et al. (2014) clearly indicated that food losses have great potential to be converted into animal feed ingredients. In this study, two food waste scenarios were proposed: the first in which food waste was destined to an anaerobic fermentation, the second one to the production of animal feed. Food waste products with low moisture content (e.g., bread or pasta) can be efficiently used to reduce the environmental impact of feed production. In fact, the study demonstrated that in ten

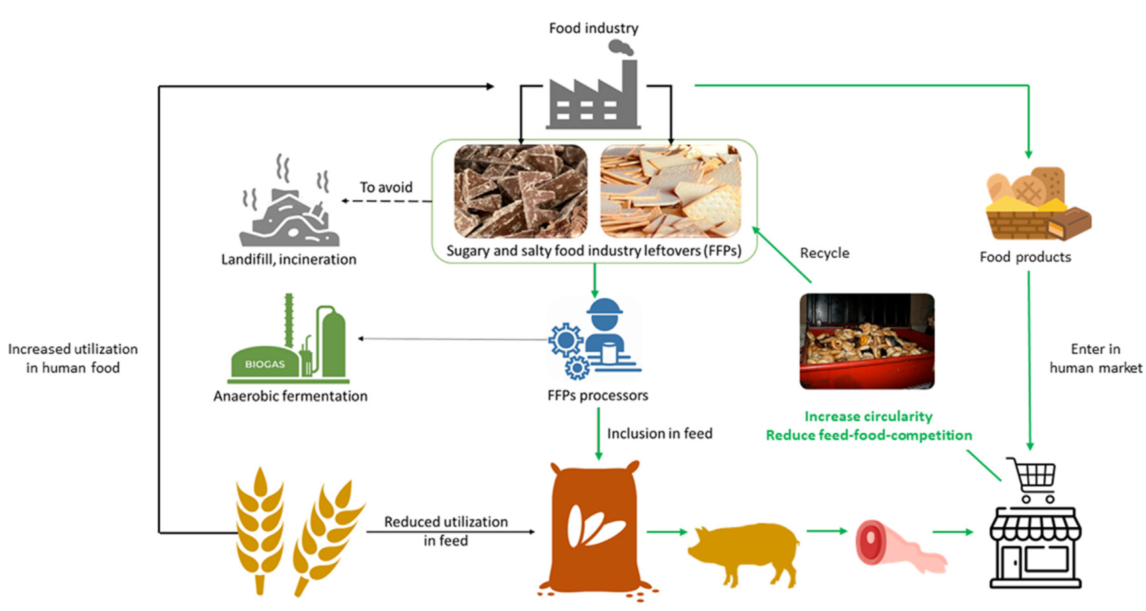

Fig. 3. Schematic representation of former food products (FFPs) as potential substitutes for common grains in the feed of pigs and post-weaning piglets.

impact categories out of twelve (metal depletion, natural land transformation, urban land occupation, agricultural land occupation, marine eutrophication, terrestrial acidification, freshwater, terrestrial ecotoxicity, etc.), dry food waste could be a sustainable solution for producing feed (Vandermeersch et al., 2014). By contrast, humid materials fit better for fermentation and other energy-producing processes and uses. In the same direction, Salemdeeb et al. (2017) stated that municipal food waste for animal nutrition purposes would lead to better environmental and health impact than processing waste by composting or by anaerobic digestion, for example in terms of reduction of greenhouse gases emissions (Salemdeeb et al., 2017).

This circular use of by-products such as FFPs could be extended to other types of food waste, or to other livestock species such as broilers, ruminants, or aquaculture, if combined with targeted nutritional evaluations and *in vivo* tests to evaluate animal response (Govoni et al., 2021 and 2022; Pinotti et al., 2021), with the aim to increase the efficiency of livestock production (Fig. 3).

Conclusions

The main FFPs currently used in animal nutrition are leftovers from the confectionery and bakery industry. These products have a high-energy content in terms of sugars, oils and starch. Pigs, as omnivorous animals, are ideally the most suited species to convert several kinds of alternative ingredients, such as FFPs, into high-quality animal protein.

In terms of safety, farmers, nutritionists, industries, and governments must pay serious attention to animal feedstuff production, considering that the quality and safety of feed are essential prerequisites for human food safety. Specifically, the level of packaging residues in FFPs as well as the microbial load of pathogenic organisms must be considered in compliance with the feed regulation.

Reducing food waste, increasing recycling, or above all enhancing ex-food management, would mitigate the environmental impact of livestock and feed production by keeping nutrients in the food chain with the production of high-quality animal protein for human consumption. Feed production from FFPs fits perfectly with the current circular economy concept. Recognising FFPs no longer suitable for human consumption as a resource rather than a waste product, the food industry could increase the amount of ex-food recycled, reducing both the amount of waste sent to landfill and the resources that would be discarded. This would help to reduce costs as well as the environmental impact of the food/feed production chain.

Ethics approval

Not applicable.

Data and model availability statement

None of the data were deposited in an official repository. Data are available upon request from the corresponding author.

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Luciano Pinotti: Conceptualisation, Writing – Review and Editing, Supervision, Project administration, Funding acquisition. **Luca Ferrari**: Writing – Original Draft. **Francesca Fumagalli**: Writing – Original Draft. **Alice Luciano**: Writing – Original Draft. **Michele Manoni**: Writing – Review and Editing. **Sharon Mazzoleni**: Writing – Original draft, Writing – Review and Editing. **Camilla Govoni**: Writing – Original draft. **Maria Cristina Rulli**: Conceptualisation, Supervision. **Peng Lin**: Writing – Review and Editing. **Giuseppe Bee**: Conceptualisation, Supervision. **Marco Tretola**: Conceptualisation, Writing – Review and Editing, Supervision.

Declaration of interest

None.

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