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Review

Recycling food leftovers in feed as opportunity to increase the sustainability of livestock production

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ABSTRACT

With the diminishing availability of farmland, climate change and the threat of declining water resources, livestock needs to meet the growing demand for food and feed by using fewer resources. The re-use of food losses as sustainable ingredients for feed formulations could represent a promising alternative to cereal grains for both monogastrics and ruminants, increasing livestock sustainability and reducing the competition between animal and human nutrition. The acceptance of food leftover for feeding animals it is still far to be completely welcomed in several countries, where the outdated stereotypical image of the garbage used as feed is still existing. To implement this practice, a renewed image of food leftover as feed is needed, mainly disseminating the most recent findings about their properties, the new technologies applied for their production and their impact on the environment. This paper aims to disseminate a wide understanding of food losses and explores the potential benefits of using two main categories of food leftovers, namely former food products (FFPs) and bakery by-products (BBPs), as alternative feed ingredients in pig and ruminant nutrition. Several characteristics of those two categories of food losses are examined and compared to a standard diet, such as nutritional-related properties, safety, efficiency and environmental implications. The literature shows that both categories of food leftovers hold a significant nutritional value and are a sustainable alternative to traditional feed ingredients. They resulted as a low risk category for animal health. In addition, when used in complete feed to replace traditional feed ingredients, neither FFPs nor BBPs do not decrease animal's growth performances. These findings valorize food losses into animal feed as a well-suited strategy to contribute to a reduced environmental and climate footprint of animal products and food waste prevention. However, a greater participation by feed/food processors and stakeholders is crucial to allow the sector to increase its contribution in the entire EU food and feed chain.

Contents

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1. Introduction

Animal feed is the largest single cost item of livestock production, accounting for 60%–85% (FEFAC, 2018) (depending on the farm species) of the total cost inputs/year (Lawrence et al., 2008). Innovative feeding and nutrition practices have become increasingly important as livestock systems strive to become more efficient and sustainable (Luciano et al., 2020). The feed industry needs then to enhance the efficiency of livestock production by reducing GHG emissions and other factors that have a negative environmental impact (Audsley and Wilkinson, 2014).

Livestock production needs to pay more attention to limit the use of natural resources per amount/unit of animal product, expressed as the footprint per product, such as the "water footprint", "mineral footprint", "land (arable or total land) footprint" (Flachowsky and Meyer, 2015). Compared to other food items, the production of animal food has a high environmental impact given that the conversion of plan biomass by animals lead to a loss of energy and proteins (Van Hal et al., 2019). The 32% and up to 68% of the yielded grains in the world and in developing countries, respectively, are being fed to livestock (Elferink et al., 2008). Feeding grains to livestock may be unsustainable due to world population growth and this leads to the research of alternative and more sustainable feed ingredients (van Zanten et al., 2015). The selection of the most appropriate raw materials and the feed formulation are two factors that can influence efficiency indicators (Pinotti et al., 2019a). There is a worldwide trend for waste reduction, including food waste reduction. This has led to an increase in the recycling and reuse of these products in the animal feed chain (Organization, 2019). Strategies and solutions, such as a "food recovery hierarchy", are thus needed to reduce the impact of feed production on the environment by reducing the use of natural resources and increasing their reuse (Mourad, 2016). Food leftovers as a cereal substitution is an example, since they do typically not compete for land consumption with food production (Van Hal et al., 2019). Several products that humans cannot eat could be suitable as livestock feed, e.g. co-products, food-waste and biomasses such as plant by-products (Pinotti et al., 2020). From a circular economy perspective, feeding ex-food to livestock or using biomass to feed livestock, referred to as 'leftover streams', could be an effective option for using resources and reducing food losses (Fausto-Castro et al., 2020) as outlined in Fig. 1. Specifically, ex-food (also known as 'former foodstuff products', FFPs), represents a sustainable and alternative energy supply for feeding animals (Pinotti et al., 2019b).

There are several terms that are used to refer the different food effluents, such as food losses, food waste, and former foods products. Food waste refers to materials that remain after, or are produced during the processing, manufacture, preparation or sale of human food. This can include different types of food biomasses and edible material intended for human consumption, arising at any point in the food supply chain, such as that collected at restaurants, retail, or from household food scraps (Gustafsson et al., 2013). Food losses refer to a decrease in food quantity or quality in the early stages of the food supply chain, thus reducing the amount of food suitable for human consumption.

The concept food losses is thus often related to post-harvest activities that lack systems or infrastructural capacities. Food waste, on the other hand, often refers to later stages of the food supply chain, such as retail and consumer households. Hence, the causes of food waste are often related to human behavior and take place in the later stages of the food supply chain (Gustafsson et al., 2013).

Former foods products and food leftovers are food effluents that are somewhere in the middle. Specifically, food leftovers are foodstuffs that were manufactured for human consumption in full compliance with food laws, but which are no longer intended for human consumption for practical or logistical reasons or due to problems of manufacturing, packaging defects or other defects – none of which present any health risks when used as feed (Gustafsson et al., 2013; Organization, 2019).

An important distinction between former foods products/food leftovers and food waste is their legal status. Former foods products can be used to feed humans or animals which does not represent a form of waste treatment; while food waste can be further processed to return nutrients to the soil, extract energy and generate heat, but cannot return to the food chain. Clearly, the animal feed chain should not be a means to dispose of degraded or contaminated foodstuffs, and that the product should have a sufficient nutritional value so that it can be considered as feed (Organization, 2019).

The evolution of livestock systems will inevitably involve a trade-off between feed security, feed safety, animal welfare, environmental sustainability and economic development (Thornton, 2010). Sustainability is not the only common denominator among many of these issues, which are often politically-sensitive (Vågsholm et al., 2020). Innovation is considered another key factor in the field of sustainable feed/food security (Pinotti and Dell'Orto, 2011). The conversion of industrial food losses into ingredients that can be employed in feed industry is regarded as a virtuous practice that should be carried out worldwide, with the aim to keep food losses -and finally nutrients-in the food chain (Georganas et al., 2020).

The potential mitigation of environmental impacts due to the use of FFPs as animal feed should also be considered. Specific life cycle assessment (LCA) studies on the reuse of FFPs in animal nutrition are still limited. One study by Vandermeersch et al. (2014) clearly indicate that food losses have great potential to be converted into animal feed ingredients. In the same direction,

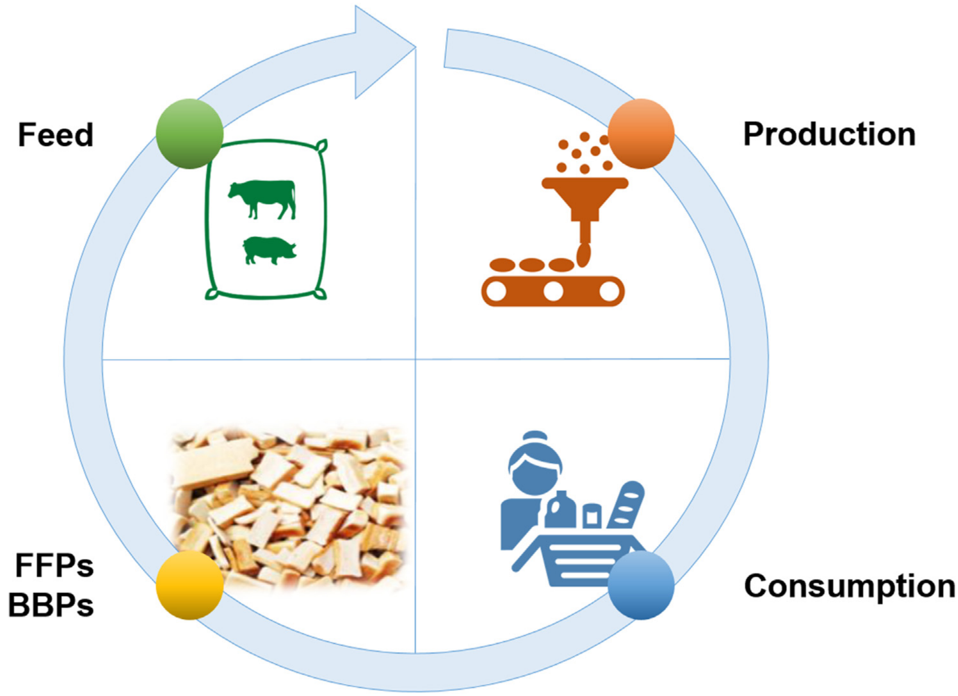

Fig. 1. The role of food losses, upgraded to feed, i.e. former foodstuffs products (FFPs) and bakery by-products (BBPs) in the circular economy.

Salemdeeb et al. (2017) investigated the use of food waste as animal feed. This study concluded that the use of municipal food waste for animal nutrition purposes would lead to better environmental and health impact than processing waste by composting or by anaerobic digestion (Salemdeeb et al., 2017). The use of food waste for animal nutrition is currently not allowed in the EU while the use of FFPs, which are not food waste, is already regulated by several authorities around the world and does not represents a regulation issue. Fig. 2 summarizes the legislation for the use of food in feed.

The use of FFPs as feed is still limited and in several countries, their processing is still in a start-up phase (Luciano et al., 2020). To allow the sector to increase its contributions in livestock sustainability, it is crucial to achieve a comprehensive science-based analysis to demonstrate the feasibility, safety and sustainability implications. The gap of knowledge about nutritional properties, safe use, legal definition and good manufacturing practices represents the main factor that limits the former foodstuff processing industry to expand in Europe. The aim of this review is to fill the lack of knowledge about FFPs to promote their use in feed. The study first examines the nutritive attributes of FFPs, processing-related properties and safety-related issue. Finally, it explores resource and environmental implications.

2. Method

The method used in this review consisted of three steps: (i) choosing key words for the literature search, (ii) using different databases to identify the suitable literature (iii) analyzing the selected literature by extracting information. These three steps are summarized in Fig. 3 and are described below.

2.1. Choosing key words

The Official Journal of the European Union (OJ) groups and lists all the ingredients used for feeding production and in particular defines former foodstuffs as "Foodstuffs, other than catering reflux, which were manufactured for human consumption in full compliance with the EU food law but which are no longer intended for human consumption for practical or logistical reasons or due to problems of manufacturing or packaging defects or other defects and which do not present any health risks when used as feed." (European Commission, 2013). This definition was updated and strengthened in 2018 by the European Commission (Fig. 2), which formulated new guidelines for the employment of former foodstuff into animal nutrition.

Very often these products are identified with names other than former foodstuffs, which is the proposed name in the European Regulation and there is no single recognized definition in the scientific literature. The major difficulty in this field is how these products are defined, since different definitions can be found in the literature.

Six different key words are the most common terms in the literature and in the data bases: (i) former food, (ii) former foodstuffs, (iii) food leftovers, (iv) ex-food, (v) bakery meal, and (vi) food waste. Former food products (FFPs) represent a wide category recently introduced by the European law (European Commission, 2013), and therefore not commonly used in the literature. The term "bakery meal", was mainly used in manuscript titles, while in the articles, they are often referred to as bakery by-products (BBPs) and bakery waste.

2.2. Identifying the literature

We used the abovementioned key words for the literature searches in three different databases: (i) Scopus, (ii) Web Of Science, and (iii) Google Scholar. After the first search the found articles were checked manually principally by reading the abstract and verifying the presence of the chemical composition of the diet/ingredients used or tested in the study.

We found many articles not in line with our topic which were thus excluded. For example in the Scopus database, we found a total of 8261 articles when searching for the word "former food", but

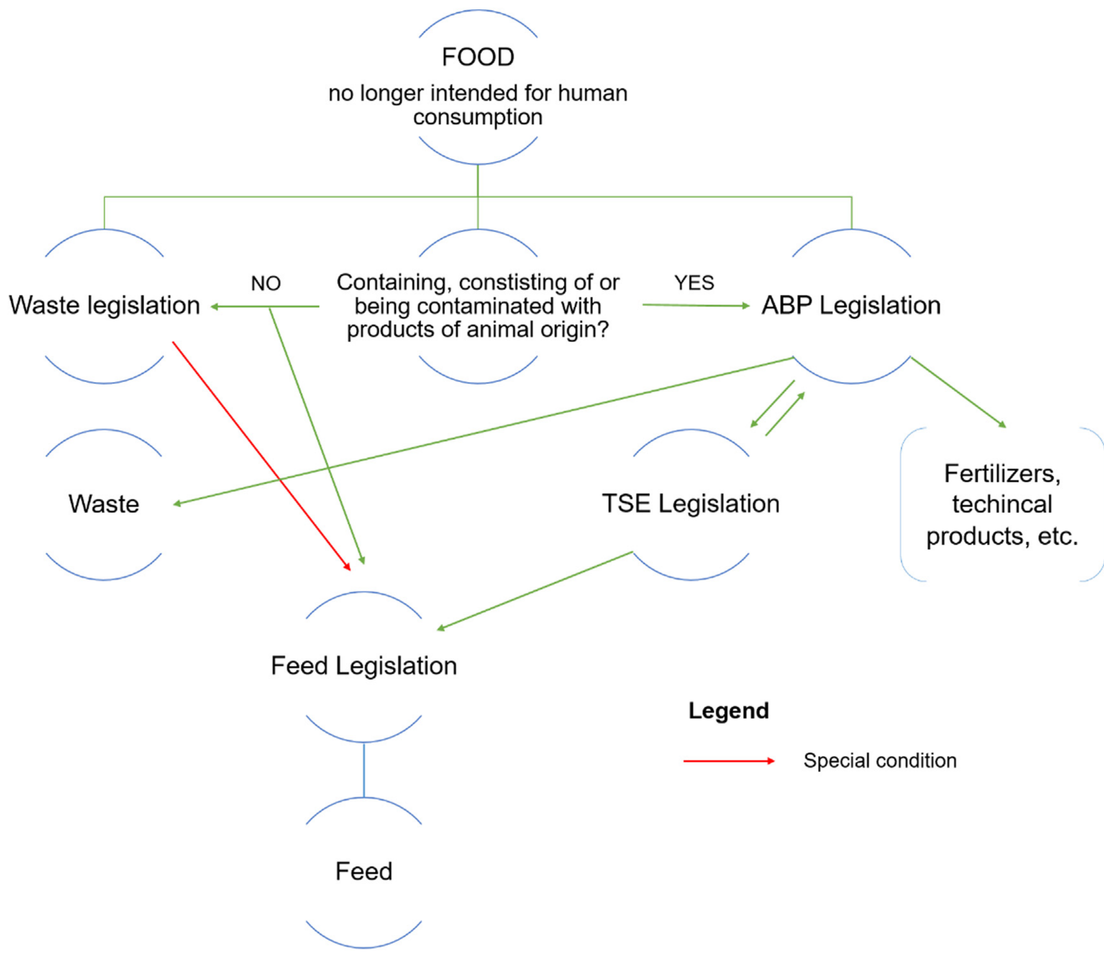

Fig. 2. Flow chart from FOOD to FEED. Adapted from: European Commission Notice, 2018.

only three articles were selected for this review and reported in Table 1. The research conducted in the different databases provided 25 articles on which this review was prepared.

2.3. Analyzing literature

The 25 selected articles were chosen for this review because they reported the chemical composition of the ex food used in animal trials. Based on the literature and the key words selected, two main categories of food leftovers were identified: former food products (FFPs) and bakery by-products (BBPs). A list of studies using the terms FFPs or BBPs are reported in Table 2.

2.4. Data analysis

In order to compare the nutrient composition of the FFPs and BBPs and the overlap and distributions between them, box plots were examined. Box plot analysis was carried out in order to calculate mean, quartiles, minimum and maximum observations and outliers of the FFPs and BBPs.

3. Main categories and nutritional properties of FFPs and BBPs

3.1. Major classes of nutrients

In the considered literature, two main categories of ex-food have been identified: FFPs and BBPs. The starting material used for their preparation defines these two types. The leftovers originated from the food industry, where bakery products such as bread and sometimes pasta are the major source of nutrients as in the case of BBPs (Nježić et al., 2010).

Confectionary products leftovers, mainly composed by sugar-rich products like biscuits, waffle and chocolate, compose the category of FFPs. Snacks and other salty materials (chips and crackers) are usually in the first category. It can thus be speculated that there are two main types of food leftover on the market, namely salty materials (i.e. BBPs) and sweet materials (FFPs), however they are sometimes mixed together.

Both FFPs and BBPs can be used as alternative feed ingredients in farm animal diets. Former foodstuff processors start from different food leftovers and after unpacking, sorting, drying, grounding and sieving are able to obtain suitable feed ingredients. The resulting material can be used to replace some of the existing raw materials in various feed formulas. Some FFPs such as candies and dairy powders can be water dissolved and processed to obtain syrups, which can replace molasses, often used as a technological (binding) agent during the pelleting of feed (Van Raamsdonk et al., 2011). Also sweet materials may be directly used. An example is Guo et al. (2015) who proposed that chocolate candy feed, containing of over 50% of simple sugars, could partially replace lactose in nursery pigs (Guo et al., 2015). Fig. 4 shows examples of packed and unpacked food leftover before being processed.

An analysis of the main composition of both FFPs and BBPs

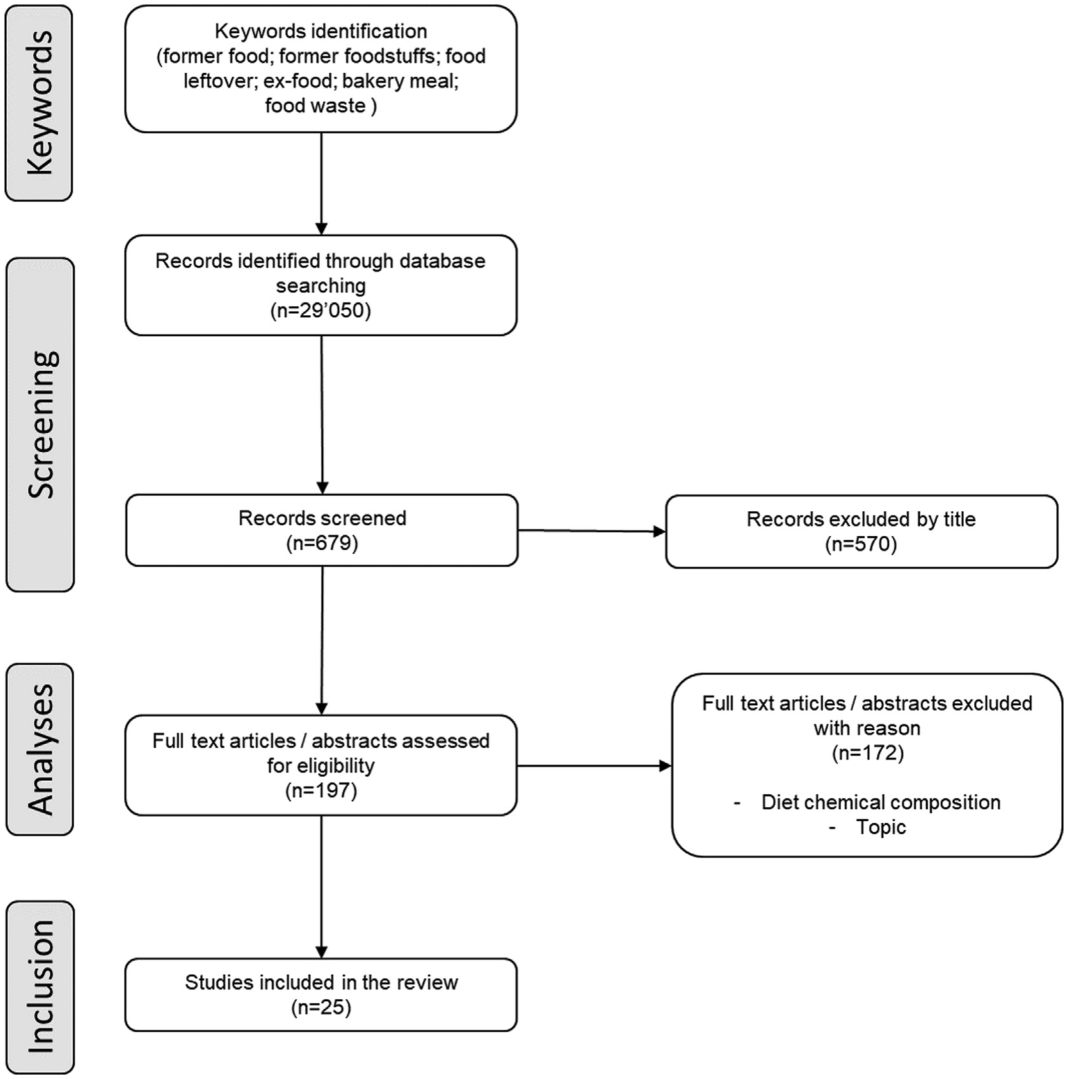

Fig. 3. The selection process for the 25 studies included in this review.

Table 1
Number of articles found in the three databases for each key word used. The table also considers articles found in more than one database.

Key words	Databases		
	Scopus	Web Of Science	Google Scholar
Former Food	3	2	2
Former Foodstuffs	3	4	3
Food Leftovers	1	0	1
Ex-Food	2	2	2
Bakery Meal	12	10	11
Food Waste	2	3	2

reported in Table 3 and Fig. 5, highlights that they have some interesting differences. Based on the latest findings (Luciano et al., 2020) and analyzing the nutritional facts reported for native products intended for human consumption, FFPs are extremely rich in carbohydrates and, depending on their origin, also in fat (Luciano et al., 2020). Among carbohydrates, simple sugars (e.g. sucrose, lactose, glucose, fructose) represent a significant quota, especially when confectionary products are considered (Guo et al., 2015). In the case of BBPs, the average nutrient concentration again indicates a high carbohydrate content [on a dry matter (DM) basis], even though in these materials fiber fractions are also detectable.

In the studies considered in the present review, crude fiber (CF), Neutral Detergent Fiber (NDF) Acid Detergent Fiber (ADF) were

Table 2
References considered in the study. FFP = former foodstuffs products; BBP = bakery by-products.

Category	Source
FFPs	(Bouxin, 2016; Dale et al., 1990; Giromini et al., 2017; Guo et al., 2015; Luciano et al., 2020; Mancini et al., 2019; Takahashi et al., 2012; Tretola et al., 2019a; Tretola et al., 2019b).
BBPs	(Adedokun et al., 2015; Almeida et al., 2011; Casas et al., 2015; Casas et al., 2018; Champe and Church, 1980; DePeters et al., 1997; França et al., 2012; Hindiyeh et al., 2011; Humer et al., 2015; Kwak and Kang, 2006; Liu et al., 2018; Mancini et al., 2019; Rojas et al., 2013; Saleh et al., 1996; Slominski et al., 2004; Sol et al., 2016; Stefanello et al., 2016; Zhang and Adeola, 2017).

Fig. 4. Examples of packaged and unpackaged former foodstuff products ready to be processed in FFP ingredients for feed production.

Table 3
Minimum value (min), maximum value (max), mean, and relative coefficient of variation (CV) of FFPs and BBPs considered in the present study. CP = crude protein; EE = ether extracts, CF = crude fibre; NDF = neutral detergent fibre; ADF = acid detergent fibre; NSC = non-structural carbohydrates; NFE = nitrogen free extractives; ME = metabolizable energy.

Items	FFPs				BBPs			
g kg^{-1} DM	min	max	mean	CV	min	max	mean	CV
CP	7.30	13.2	10.6	0.15	2.10	16.7	11.4	0.40
EE	4.80	15.0	9.80	0.23	0.30	12.2	6.50	0.51
CF	0.50	5.20	2.60	0.54	0.50	13.4	3.60	1.36
NDF	5.40	22.6	12.1	0.47	2.10	50.5	20.5	0.80
ADF	1.20	6.80	3.20	0.57	0.40	22.1	7.90	0.80
Ash	1.40	8.20	3.40	0.52	0.70	8.60	4.90	0.46
NSC	50.6	79.3	64.7	0.13	60.1	78.9	65.7	0.11
Starch	41.9	73.4	50.9	0.22	24.0	86.3	44.7	0.43
NFE	60.8	79.0	69.4	0.08	75.5	77.9	76.7	0.02
ME, MJ kg^{-1} DM	14.5	18.2	16.4	0.07	11.4	19.0	14.6	0.16

always higher in BBPs than in FFPs. Bakery by-products showed on average a +40% CF content (on a DM basis), +70% NDF and +140% ADF content as shown in Table 3 and Fig. 5. These figures indicate that BBPs consist of a mixture of food ingredients originating from flour or whole cereal grains and with some high-fiber ingredients, such as bran or other co-products (Liu et al., 2018).

The fat content is another of the main differences between FFPs and BBPs. In Table 3 can be observed that FFPs considered in the present review showed 45% more fat than BBPs. These aspects have been extensively addressed in different studies and reviews (Giromini et al., 2017; Luciano et al., 2020; Pinotti et al., 2019a, 2019b; 2019c) which report that FFPs have a similar nutritional composition to common cereal grains, but are generally characterized by a higher fat content that also usually affects their energy density (expressed as metabolizable energy, ME). This higher ME content in FFPs (+12%) in comparison with BBPs, was also observed in the present study. By contrast, the protein content in both FFPs and BBPs was comparable.

In terms of the starch and Non-Structural Carbohydrate (NSC) content, the situation is more complex. While the starch content in FFPs was slightly higher (+13%) than in BBPs, the NSC content was similar in both categories. The values recorded in Table 3 indicate that the partial contribution of different carbohydrates in defining NSC, in FFPs and BBPS, was variable. In fact, the difference between NSC—Starch in FFPs and BBPs was about 14 g/100 g and 20 g/100 g, respectively. The main reason for this is what the NSC fraction represents. NSCs are calculated by difference [100-(%NDF + %CP + % Fat + Ash)], which means that NSC fraction is heterogeneous. Indeed, it is composed of different amounts of simple sugars, beta-glucans, galactans, and pectins. Combining the contents of these fractions (NSCs and starch) with the fiber fractions (CF, NDF, and ADF), in FFPs the simple sugar content would seems to be higher (Guo et al., 2015), while in BBPs, the main contributors are beta-glucans, galactans, and pectins derived from the whole grains often used in modern bakery products (Liu et al., 2018).

When compared to the feedstock, both FFPs and BBPs are characterized by a more variable nutrient profile, according to the specific materials/samples tested. An example is the starch content, which was observed to fluctuate within a range of 25%–73%, with rare outliers, as well as the digestible energy, which ranged from 11.0 to 19.0 MJ kg^{-1}. The highest variability was observed for BBP, NDF and ADF contents, which ranged from 2% to 50% (on DM basis), and from 0.2% to 20%, respectively. Those data are summarized in Fig. 5.

These findings are in accordance with the literature. In a study by Giromini et al. (2017), the average values of specific FFPs in terms of EE, NDF and CF contents were 10%, 5.4% and 4.5%, respectively

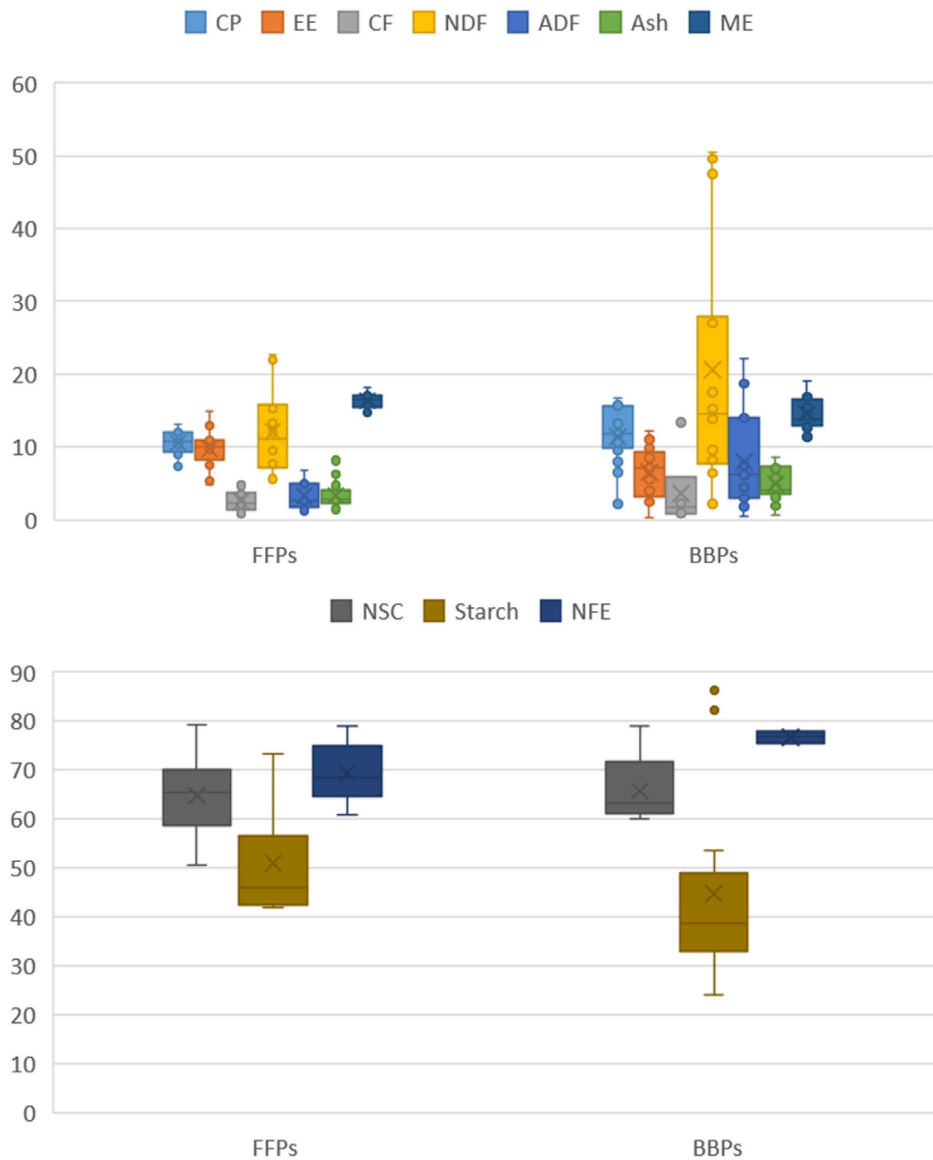

Fig. 5. The various Former Foodstuffs Products (FFPs) and Bakery By-Products (BBPs) considered in the study. Each box plot reports the mean (×), median (–), minimum and maximum observations and outliers in the two classes of samples (FFPs and BBPs). Data ere expressed in g/100 g on DM for main nutrients, and in MJ/kg on DM for metabolizable energy. Abbreviations: CP = crude protein; EE = ether extract; CF = crude fibre; NDF = neutral detergent fibre; ADF = acid detergent fibre; ME = metabolizable energy; ash; are reported in the upper part. NSC = non-structural carbohydrate; starch; NFE = nitrogen free extractive; are reported in the lower part.

(Giromini et al., 2017). I another study, the EE content of different bakery leftovers has been found to be around 7.5%–9.4% (DePeters et al., 1997); the NDF can also vary widely, with values of 17.9% in a bakery product analyzed by DePeters et al. (1997). A similar observation was found for the CF, which was 1.3% in bakery by-products assessed by Kwak and Kang (2006).

A further aspect is food leftovers digestibility. Both FFPs and BBPs have shown high (>80%) *in vitro* organic matter digestibility values (Giromini et al., 2017), but these values were obtained by testing FFPs and BBPs as single ingredients. A further step in the nutritional evaluation is to assess their digestibility (*in vitro*) also when these materials are used/included in pig feed. Both organic matter digestibility (Tretola et al., 2019b) and carbohydrate digestion kinetics (Ottoboni et al., 2019) were higher in diets containing FFPs (30% of inclusion) in comparison with conventional diets.

To sum up, the nutrient composition in FFPs and BBPs can be variable, which is also typical of standard/common feed ingredients. The variability in ingredients in crops is due to genetic or pedoclimatic conditions, agronomic factors, harvest and storage conditions (Gagiu et al., 2018). Both FFPs and BBPs are affected by an extra source of variability, i.e. the processing (Zijlstra, 2006). Although this great variability in FFP/BBP products can be a challenge for the feed formulation, it still offers interesting flexibility in formulating ratios according to the nutrient/energy requirements of the target animals (NRC, 1998).

The experience acquired by FFPs and BBPs processors after many years spent on the analyses of inbound products led to the possibility to predict the range in variation among different sources of products and also among the same source and different loads (Tretola et al., 2019a). It has been observed that variations between different geographical regions are relatively small in terms of the chemical composition of bakery meals (Liu et al., 2018). These findings allowed the processors to produce raw materials with very low coefficients of variation, where these average values can be used to predict concentrations of nutrients in bakery meals (Liu et al., 2018). The final feed products are produced starting from raw materials, whose nutritional data are very reliable for producers and which are assessed by analyses of final products and standards. Assuming the ability of FFPs/BBPs processors to overcome the issue of variability in FFPs/BBPs at the industrial level (during FFP preparation), a further step in the nutritional evaluation of FFPs is a better understanding of their functional/dietetic properties.

3.2. Processing-related properties of FFPs and BBPs

Digestibility is strongly affected by feed dietary factors such as nutrient composition and feed processing (Temesgen et al., 2017). Processing is a fundamental step for FFPs and BBPs prior to their utilization in animal nutrition, because it facilitates the incorporation in animal diets (Georganas et al., 2020). Many ingredients of FFPs and BBPs, such as cereal flours, eggs, sugar and fats are usually mixed with water to form a dough or batter (Bushuk, 1986), and then subdivided into portions for the second stage of processing, i.e. cooking (Bushuk and Scanlon, 1993). Both industrial and domestic cooking can modify the chemical and physical characteristics of food (Klopfenstein, 1980), thus affecting the macro- and micronutrient bio-accessibility and bioavailability.

Due to their increased water absorption capacity, extruded wheat flours are an opportunity to increase bread output in bakery production. Potential issues could be the starch gelatinization, increased damage to the starch content, together with a reduction in lipid oxidation due to enzyme inactivation, an increase in soluble fiber and a reduction in thermolabile vitamins, anti-nutritional factors and microbial load (Klopfenstein, 1980).

Thermal processing can also modify ingredient's digestibility. High-temperature treatments, in fact, can improve digestibility values by the protein denaturation of anti-nutritional factors such as the anti-tryptic activity of raw soybeans (Giuberti et al., 2014). In some cases protein digestibility can be reduced by thermal protein aggregation (Ercolini and Fogliano, 2018). Other processing techniques such as solvent extraction or cold press, can lead to an increased variability in the values of energy content (Spragg and Mailer, 2007).

Unlike the untreated feed ingredients commonly used in livestock production (Giuberti et al., 2014), FFPs and BBPs typically undergo to both mechanical and thermal processing (Singh et al., 2010) that affect the nutritional properties of the diet, in particular the starch fraction. Table 4 summarize the effects of various processing techniques on starch digestibility.

The processing of FFPs and BBPs can strongly affect their nutritional characteristics and, subsequently, the resulting feed. An example is the glycemic index of processed starchy food, which can be used to classify starchy ingredients (Giuberti et al., 2012). Ottoboni et al. (2019) recently evaluated both the predicted glycemic index (pGI) and hydrolysis index (HI) of FFPs. This study revealed that in FFPs, both indexes were higher than for unprocessed corn. In terms of chemical composition, the HI and pGI of FFPs also seemed to be related to the nature and the processing of the various FFPs, with a high variability among different samples (Ottoboni et al., 2019) (Ottoboni et al., 2019). The high availability of simple sugars in FFPs represents one of the most interesting characteristics of those alternative feed ingredients, especially when used to formulate diets for young animals feeding. Several studies in humans (Holt et al., 1992; Lavin and Read, 1995; Ludwig et al., 1999) have suggested that the ingestion of high-GI meals increases hunger and promotes overeating in subsequent meals compared to low-GI meals, which is a positive effect in terms of pig nutrition.

Beside the starch content, margarine, butter and partially-hydrogenated vegetable oils characterize bakery products as the main fat source. Given that bakery and pastry products are often composed of a high percentage of saturated fatty acids (Albuquerque et al., 2017), the effect of these types of fats on animal performance and product quality need to be assessed, as was done for pigs (Raj et al., 2017).

4. Safety issues

Using FFPs and BBPs in animal feeding also entails safety issues to ensure a safe inclusion in animal diets. Although FFPs and BBPs have several similarities, safety issues have been mainly addressed for FFPs, probably because BBPs are usually obtained by unpacked and more stable ingredients compared to FFPs. In the FFP safety evaluation, two main categories of risks need to be considered during and after processing. In this paragraph, two main aspects related to the safe use of food leftover as feed ingredients will be considered: the microbial load of the final products and their potential contamination by scrapes of different materials arising from their packaging.

4.1. Microbiological load of food leftover used as feed ingredients

Complying with the EU threshold levels regarding the quantity of microorganisms found in food material is crucial before put it on the market. The same goes for the use of food leftovers in feed. Tretola et al. (2017) evaluated the microbiological load in various alternative feed ingredients. Microbiological analyses showed the very high hygienic wholesomeness and safety of all the samples examined (Tretola et al., 2017). An example is given by the mean total viable count (TVC) that was 4.92 ± 0.25 Log CFU/g, in line with the EU standards. In all the samples, the microbial load was always below the threshold limit set by the Health Protection Agency (2009). The low moisture content of those products, together with the thermal processing to which both FFPs and BBPs undergo during their conversion in feed ingredient, may have contributed in achieving these standards. Based on that, we speculate that FFPs and BBPs can be considered safe from the microbiological point of view when used in animal nutrition.

4.2. Contamination due to presumed remnants in the packaging

When FFPs or BBPs start the conversion process into feed ingredients, not the entire packaging is removed manually before the processing but is ground together with the food. Then, most of packaging remnants are mechanically removed as described in Van Raamsdonk et al. (2011) and summarized in Fig. 6.

After mechanical packaging removal, packaging remnants of different sizes have been found (Tretola et al., 2017). The most common packaging materials of food products are plastics, paper, cardboard and aluminum foil (Amato et al., 2017). Packaging materials are often manufactured using adhesives with printing on the outside (Tretola et al., 2019b). Plastics are made by the polymerization of monomers and several additives may be added to obtain the physical or chemical properties of the plastics, such as fillers, polymeric additives, light stabilizers, optical brighteners, and antistatics (Van Raamsdonk et al., 2011). The contamination levels reported in different studies (see Pinotti et al. (2019a) for references), however, were always significantly below the tolerance level proposed by the feed/food authorities (European Commission, 2011), indicating that the issue of packaging remnants is limited.

Table 4
Starch digestibility related to the processing technique applied. a Expressed as rapidly and slowly digestible starch (%); b Expressed as starch digestibility (%); c Expressed as hydrolysis index (%). Adapted from (Singh et al., 2010).

Processing	Starch digestibility	Reference
Baking	7.2[a]	Roopa and Premavalli (2008)
Frying	11.2[a]	
Toasting	31.8[a]	
Puffing	33.4[a]	
Cooking	34[a]	
Roasting	37.2[a]	
Pressure cooking	42[a]	
Sheeting of pasta (3 passes) dough (3 passes)	156[a]	Kim et al. (2008)
Sheeting of pasta (45 passes) dough (45 passes)	217[a]	
Extruded beans	306[b]	(Alonso et al., 2000; Capriles et al., 2008)
Extruded amaranth seeds	93[c]	
Cooked amaranth seeds	96[c]	
Popped amaranth seeds	112[c]	
Flaked amaranth seeds	120[c]	

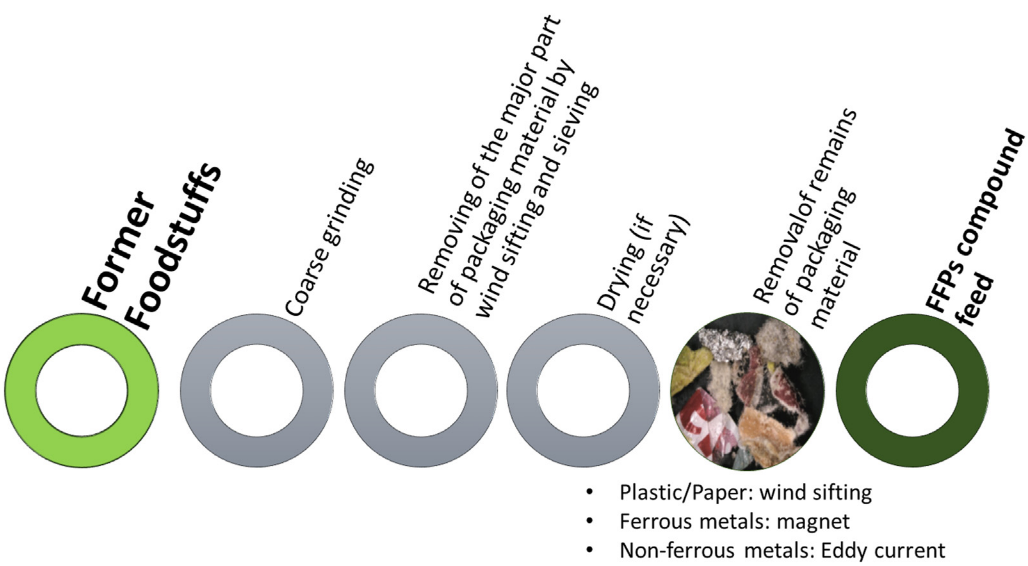

Fig. 6. Steps by which packaging is removed from food during FFPs processing.

5. FFPs and BBPs in pig nutrition

The use of alternative feedstuffs, and especially food leftovers, is not new for the pig industry (Chen et al., 2009; FEFAC, 2005). Several studies (Almeida et al., 2011; Kwak and Kang, 2006; Rojas et al., 2013; Tretola et al., 2019a; Tretola et al., 2019b) have investigated the use of food leftover in pig diets, with special emphasis not only on pig production, but also sustainability. These studies have revealed that both FFPs and BBPs can affect pig yield in different ways. Of these, variations in diet digestibility is probably the most important: both BBPs and FFPs used as cereal substitutes have increased diet digestibility and thus improved pig efficiency (Tretola et al., 2019b). In terms of BBPs, other reported side effects are related to specific nutrients such as amino acids and minerals. Compared with corn, BBP meal has been found to have a reduced digestibility in terms of all indispensable amino acids (AA) (Stein et al., 2007), a poor source of digestible AA (Almeida et al., 2011), and inconclusive results in terms of phosphorous (Rojas et al., 2013). This mineral is essential for both humans and animals. However, for practical resound this aspect cannot be addressed in the present review. Although traditional ingredients, such as corn, can be substituted with BBP meal in pigs' diets, their use merits a specific dietetic evaluation in order to optimize both the grow performance and gut health.

In terms of FFPs, the results are comparable to BBPs. Studies revealed that when FFPs are included in a diet for growing pigs this diet resulted more digestible compared to a standard diet, probably due to the partial replacement of unprocessed starch with FFPs consisting of thermal processed ingredients (Tretola et al., 2019b). Food processing and the related nutrient digestibility/availability, together with the presence of high amounts of simple sugars, may also affect animal gut health and microbiota (Knudsen et al., 2012).

Animal wellbeing and performances mainly depends by the gut health. It is thus important to investigate the effects of FFPs and BBPs, which have highly digestible starch and a high content of simple sugar on gut microbiota in piglets. Feeding post-weaning piglets with a highly digestible ex food-based diet seems to increase the instability and decrease both the abundance and the heterogeneity (biodiversity) of the gut bacterial population, compared to piglets fed with a standard diet (Tretola et al., 2019a).

As previously discussed, high digestibility is a characteristic of both FFPs and BBPs due to processing-related modification such as starch gelatinization and protein denaturation. The amount of undigested nutrients reaching the large intestine of pigs fed FFPs/BBPs-based diets is lower compared to animal fed unprocessed raw materials. This difference could lead to a different relationship between food processing/digestibility and gut microbiota, as summarized in Fig. 7.

This means that compared to traditional diets, designing feed for pig nutrition by including FFP/BBP products with a high nutrient bio-accessibility could result in a high bioavailability of proteins, carbohydrates and lipids for the pigs. This would then lead to a higher calories' absorption for the host and a lower amount of nutrient delivery to the gut microbiota. The performance of growing or finishing pigs could therefore be affected.

A reduction in bacterial abundance and biodiversity could lead to several detrimental aspects such as decreased calories extraction from undigested feed material, but also to infections from opportunistic enteric pathogens and an immature immune system (San Yeoh and Vijay-Kumar, 2018). On the other hand, the reduction in gut bacteria abundance and diversity could also lead to a reduced competition for nutrients between bacteria and the host. Fewer bacteria means a decreased activation of the immune system and a lower energy use to prevent the overgrowth of the bacterial population, which can cause a variety of detrimental conditions (San Yeoh and Vijay-Kumar, 2018).

Based on the information mentioned in this review, it is crucial to take into account the potential effects of FFP and BBPs on intestinal microbiota when used in pig nutrition.

6. FFPs and BBPs in ruminant diets

There is a lack of information regarding the effects of FFPs/BBPs on ruminal fermentation and microbiota when included in ruminant diets. As already mentioned, FFPs/BBPs are usually rich in energy due to their high content of sugars, oils and starch. This energy sources profoundly affects the rumen fermentation. Sugars are water-soluble carbohydrates that are readily available in the rumen and are thus considered as highly-fermentable carbohydrates. Sugars in fact, ferment faster than starch or fiber in the rumen, although the rates of hydrolysis and fermentation vary greatly depending on the type of sugar and rumen environment. Despite rapid fermentation in the rumen and their potential to provide greater fermentable energy to enhance microbial protein production, feeding sugars as a starch substitute in ruminant diets may not necessarily lead to extensive acid production and low rumen pH (Oba, 2011). Factors such as the amount of high-sugar feedstuffs included, the synchrony of rumen fermentation (high-sugar diets with high soluble protein), basal diet composition and ingredients, seem to be essential in terms of the potential of this material. Especially in dairy cattle, feeding high-sugar diets often increases DM intake, butyrate concentration in the rumen, and milk fat yield (Oba, 2011).

Some of these aspects have been addressed *in-vitro* by (Humer et al., 2018) using BBPs in a protocol that mimics the rumen physiology. Diets that include high levels of BBPs (30–45%) have shown a better *in-vitro* rumen degradation of starch, while the degradation of crude protein and fiber decreased. At the same time the production of methane and the ammonia concentration decreased. The rumen fermentation was also altered towards the production of propionate at the expense of acetate and butyrate. Butyrate decreased linearly with the increasing inclusion of BBPs. As expected, these changes were associated with a different rumen microbiota. The inclusion of BBPs at up to 30% of the DM had no detrimental effects on pH, fiber degradability and ruminal microbiota, and enhanced propionate production.

A higher inclusion level (45%) reduced rumen microbiota biodiversity, impaired ruminal fermentation and fiber degradation, thus making these inclusion levels unsuitable (Humer et al., 2018). One effect of including BBPs in the diet on the ruminal microbiota is that the higher starch digestibility in BBP diets increases the abundance of the Prevotella genus, a major propionate producer, leading to an increased proportion of propionate observed in the BBP diets (Humer et al., 2018). Another effect is the increased abundance of Megasphaera taxa due to the high content of rapidly-digestible carbohydrates in BBP diets. This taxa is a soluble sugar fermenter which is often correlated with a decreased lactic acidosis. This effect is probably correlated to the ability of Megasphaera to convert ruminal bacteria-produced lactic acid into acetic and propionic acids (Humer et al., 2018). Probably due to the high fat content and unsaturated fatty acids (e.g. oleic acid) of BBPs, compared to the conventional ingredients used in ruminant diets, the inclusion of BBPs also decreased the abundance of fibrinolytic bacteria *in-vitro* (Humer et al., 2018). Both the high fat content and

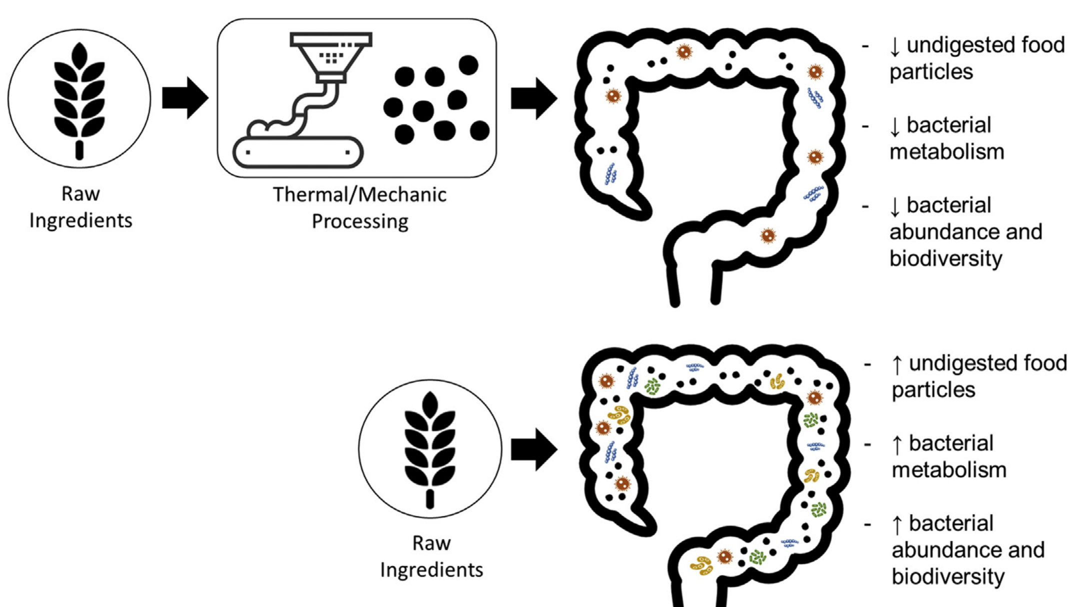

Fig. 7. Potential relationship between food processing/digestibility and gut microbiota.

high concentration of unsaturated fatty acids, in fact, have been shown to have a negative effect on the growth of such bacteria (Enjalbert et al., 2017). A recent *in vivo* study (Kaltenegger et al., 2020) reported that the inclusion of 15 or 30% of BBPs in mid-lactating dairy cows' feed increased energy density of the diet; these results were obtained increasing the fat and sugar content while reducing the starch and neutral detergent fiber concentration (i.e. shift in nutrient profile from glucogenic to lipogenic). The inclusion of BBPs in the diet enhanced not only DM intake (average 7%), but also milk yield (+5% in 15% BBPs and +12% in 30% BBPs compared to the control group). Under these conditions any case of clinical rumen acidosis has been observed: the time for the pH to fall below 5.8 (used as an index of rumen acidosis) was lower in cows fed BBPs compared to the control diet (−39% in 15% BBPs, −15% in 30% BBPs), suggesting that 15% BBPs diet had the lowest risk for developing rumen acidosis, followed by 30% BBPs diet and control diet. This therefore indicates that the rapid disappearance of sugar *per se* does not necessarily lead to an extensive fermentation acid production (Kaltenegger et al., 2020).

It has also been suggested that changes in the nutrient profile in the diet due to the inclusion of FFPs/BBPs can improve production without major detrimental effects on rumen health in dairy cows (Aljerf et al., 2018). The inclusion of FFPs/BBPs may thus represent alternative energy sources for lactating dairy cows in order to increase the dietary energy, with the limited risk of rumen acidosis However, the physiological mechanisms and effects of FFPs/BBPs on ruminant productivity merit further investigations.

To the best of our knowledge, only one *in vivo* study has tested the effects of including bakery by-products in sheep diets. In this study BBPs replaced the corn meal in different proportions (specifically 25, 50, 75 and 100%) (França et al., 2012). The authors observed no effects of BBP inclusion on the nutrient intake and digestibility, nor on the nitrogen balance, pH values or concentration of volatile fatty acids. However, due to the higher ruminal availability of energy, which allows a greater use of ammonia for microbial growth, the ammonia nitrogen concentration showed a negative correlation to the level of BBP inclusion. The authors concluded that BBPs can safely replace corn meal in concentrate rations in sheep diets (França et al., 2012).

7. Environmental implications

A sustainable livestock production is essential in the current world, in which global population is growing together with food demand. The sustainability is intended in terms of an increase in livestock productivity, a reduction in resources consumption and in GHG, not to mention an increase of animal health and food security. The livestock production sustainability is strictly correlated with sustainable agricultural development, because in order to face with an expected increase in consumption of animal-source food, several virtuous approaches can be adopted to increase crop yield, cropping intensity and a limited expansion of land use. An example is to improve resource efficiency through the adoption of agricultural practices and technologies by smallholders that currently are only the prerogative of the largest producers. These practices are the employment of feed substitutes such as by-products or food leftovers, the energy and water recycling and a more careful use of grazing land. These latter could provide a more sustainable livestock sector, whose animal-source products contribute to the supply of high-quality proteins, thus ensuring food security (HLPE, 2016; Vågsholm et al., 2020). In this direction the development of a long-term sustainable agriculture is mandatory, and the use of food leftovers as feedstuffs should be considered, since it can reduce the competition between human and animal diets (Vågsholm et al., 2016). Although the use of food leftovers is regarded as an innovative practice in sustainable animal nutrition and circular economy, the aspect of food safety must be considered. The main risk linked to the re-entering of food leftovers in the feed-food chain is to recycle and accumulate biochemical hazards, even pathogens. For this reason the management of food leftovers cannot be distinguished from food security and food safety. Food leftovers originate from food produced and intended for human consumption, which is usually inspected and supervised to ensure safe and contaminant-free products. Although there could be present contaminants or packaging remnants in food leftovers used in animal feeding, they are below the permitted threshold limit set by the Health Protection Agency (2009).

To our knowledge, there is a lack of studies about the assessment of the sustainability features associated with the use of food losses for livestock purposes. A number of studies using life cycle analysis (LCA) considered food waste but not food leftovers for livestock feeding (Dou et al., 2018; Tallentire et al., 2018; Van Hal et al., 2019). As stated before, there is an important legal difference between food losses and food waste, the latter forbidden by the EU law as livestock feed (Zu et al., 2016). FAO clearly clarified the differences between food losses and food waste stating that "food losses represents the decrease in quantity or quality of food in the production and distribution parts of the Food Supply Chain (FSC) mainly caused by the functioning of the food production and supply system or its institutional and legal framework" (Bellù, 2016). Contrastively, food waste is "part of the food loss which refers to the removal from the FSC of food (whether processed, semi-processed or raw) which is fit for consumption, by choice, or which has been left to spoil or expire as a result of negligence by the actor, predominantly, but not exclusively, the final consumer at the household level". Food losses are then something undesired, occurred by inadequate technology, poor logistics etc. Strategies and policies to reduce food losses have to be different from those aimed to reduce food waste. Differences between food losses and food waste exists also considering their environmental implications. Taking into account LCA studies on the use of food waste for animal nutrition purposes, they need to be treated before being used, requiring additional energies and resources (Kim and Kim, 2010). Has been observed that if used as feed instead of being sent to the landfill, food waste would produce less GHG emissions. Quantitatively, 200 kg CO_2-eq per ton of dry-based treated food waste, 61 kg CO_2-eq per ton of wet-based treated food waste versus 1010 kg CO_2-eq with landfill (Kim and Kim, 2010). The inclusion of FFPs in animal diets do not requires the same pre-treatments as in the case of food waste, therefore the values of GHG emissions related to the feed-making process would be likely lower compared to food waste. However, more studies focused on food leftovers are needed from this point of view.

Vandermeersch and co-authors (2014) compared the environmental footprint of "bread waste" when used to produce former foodstuff or processed for biogas production. The study realized that the conversion of the bread leftover into animal feed was the most sustainable option. Those results could be case sensitive and need to be analyzed carefully, but they clearly determine the great potential of food leftover to be converted into animal feed ingredients. The use of FFP or BBP in animal diets might represent also an opportunity for generate "new circular production system" in which smallholders are involved. The connection between farm (smallholders) and small or medium local retails indeed, can be implemented, creating conditions for keeping some food leftover in the food chain. Intuitively, in such scenarios BBPs seems to be with higher potential than other material, since well known (e.g. bread) and often ready to used. Such innovations can increase not small farm productivity but also can help smallholders, to reach the market (connection with small and medium retails), that could ameliorate the condition of small communities.

Aside from the improved climate footprint, also other resources could be saved by replacing grains with FFPs. The soybean represents the world's primary plant protein, and 85% of all soybeans are cultivated for feed purposes, primarily for pigs and poultry (Organization, 2018). These protein sources require large arable lands and a huge consumption of water for their growth. At the same time, cereals comprise the largest share of global food loss and waste by caloric content (53% of the total) (Lipinski et al., 2013). This inefficiency could be moderated by replacing grains with FFPs, leading to a corresponding reduction in the use of resources correlated with grain production such as energy, fertilizer, water and land. In the U.S. 110−140 m3 water and 17 kg N fertilizer are used to produce 1 t maize grain (Kim et al., 2014). The replacement of a certain percentage of maize with the alternative energy source represented by FFPs could generate a substantial drop of the livestock environmental impact.

The use of FFPs-based diets could also impact the cost of livestock production. Studies observed that European pork production costs €1.4 to the farmer but €1.9 of damage to the environment per kg of pork meat produced (Nguyen et al., 2012), where those environmental costs are primarily related to the processes of feed grain production (Salemdeeb et al., 2017).

Further quantitative assessment are necessary to fill the gap of information about the environmental effects on the use of food losses for livestock feeding. The knowledge on the potential environmental benefits of food leftovers could raise the interest and therefore the use of those products in animal diets, with a consequent improvement of the livestock sustainability.

8. Conclusions

The present review evidences that unsold or defected pasta, bread, chocolate and candies can produce distinct food leftovers products that, when mixed together, can result in uniform products/meals named former food products (FFPs) and bakery by-products (BBPs). To our knowledge, this review for the first time propose a different definition for FFPs and BBPs, in order to facilitate their use in the livestock sector and to highlight the most important characteristics of both classes of food losses. For the first time the nutritional properties, safety issues and effects on pig and ruminant nutrition of both FFPs and BBPs are investigated by literature review. These two categories possess several similarities but also some category-specific features and once quality is assured, nutritionists can safely use them in balanced diets for monogastrics and ruminants, without impairing the productive performance (daily gain, milk yield etc.) and welfare. The exact inclusion levels however, should be verified carefully. The results discussed in this review highlight how the feed industry could give to this sector the potential to obtain the best of the nutritional and economic added value by using non-human-edible by/co-products in accordance to the circular economy principles. Both FFPs/BBPs represent an appealing opportunity to mitigate the impact of the livestock sector on the environment by converting food losses into animal protein food. Replacing traditional feed ingredients with FFPs/BBPs could also lead to a reduced competition between humans and food producing animals for raw materials such as wheat. This review also evidences that the potential of these products are not yet fully exploited as added-value products for animal nutrition. In fact, there is a lack of information on the effects of a diet containing high percentage of FFPs or BBPs on carcass composition/milk composition and rumen/gut health in growing and finisher animals, together with an assessment of the sustainability features associated with the use of FFPs/BBPs in animal nutrition. The idea to use food leftover for feeding animals is still far to be completely welcomed by livestock producers. A wider dissemination of the potential of those products, together with a renewed image of FFPs and BBPs far from the stereotypical image of the garbage, could increment their acceptance for a practical use as feed. Some logistical concerns should be considered for the food leftover collection and transport, since leftovers collection by former foodstuffs processor from companies located abroad would decline the sustainable potential of this practice. Life cycle cost analysis should be performed to clarify if the conversion of food leftover is cost-effective for both the livestock producers and former foodstuffs processors. Those surveys should also take into account the socio-economic effects, potential technological improvements, feedbacks from stakeholders, livestock producer and consumers, allowing the adoption of better-shaped strategy to increase the acceptance on the use of food leftovers in feed. This review contributes in defining an accurate picture on the nutrient profile and the safe use of FFPs and BBPs. Such information is critical for a proper inclusion of food leftover in a standardized feeding practice in the modern animal production system. The present study aimed to fill the gap of knowledge about potentials of food leftover in animal nutrition, but much remains to be done to allow the sector to increase its contribution in replacing natural resources with food losses. Hence, the livestock sector could reduce the food waste accumulation, the competition for natural resources and the environmental impact of the animal production systems.

Declaration of competing interest

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

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