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Management of meat by- and co-products for an improved meat processing sustainability

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ABSTRACT

Large amounts of meat by- and co-products are generated during slaughtering and meat processing, and require rational management of these products for an ecological disposal. Efficient solutions are very important for sustainability and innovative developments create high added-value from meat by-products with the least environmental impact, handling and disposal costs, in its transition to bioeconomy. Some proteins have relevant technological uses for gelation, foaming and emulsification while protein hydrolyzates may contribute to a better digestibility and palatability. Protein hydrolysis generate added-value products such as bioactive peptides with relevant physiological effects of interest for applications in the food, pet food, pharmaceutical and cosmetics industry. Inedible fats are increasingly used as raw material for the generation of biodiesel. Other applications are focused on the development of new biodegradable plastics that can constitute an alternative to petroleum-based plastics. This manuscript presents the latest developments for adding value to meat by- and co-products and discusses opportunities for making meat production and processing more sustainable.

1. Introduction

The meat industry generates large volumes of by- and co-products like blood, bones, skin, trimmings, organs, viscera, horns, hoofs, feet, and skull among others during slaughtering and meat processing and must be treated and disposed ecologically. For instance, near 330 million animals (cattle, sheep, pigs and goats) are slaughtered in the European Union every year resulting in the generation of more than 18 million tons of meat by-products (EFPRA, 2020a) that need to be managed in order to get better sustainability.

International Regulations are strict for the treatment and handling of meat by-products to avoid crisis like the spongiform encephalopathies (Ofori & Hsieh, 2014). In the case of the European Union, Regulation (EC) 1069/2009 (EC, 2009) and its implementing Regulation (EC) 142/2011 (EC, 2011) provided the rules for animal by-products and derived products not intended for human consumption. In the United States, the Food and Drug Administration (FDA, 2004) also provided rules for preventing the bovine spongiform encephalopathy (BSE), including a prohibition of specified risk material consisting of high-risk, cattle-derived materials that can carry the BSE agent. According to their risk to human or animal health, non-edible animal by-products were structured into 3 categories in the European Union (EC, 2009). So, category 1 has the highest risk and products under such category are used for fuel combustion or biodiesel generation; category 2 still offers a high risk and its products are used for fuel, biodiesel, biogas or as fertilizers, while category 3 offers the lowest risk and is fit for human consumption at the point of slaughter although may not be intended for human consumption either because of its non-edible content or for commercial or cultural reasons. Blood from non-diseased ruminants obtained in slaughterhouses falls within this 3rd category. These Regulations implied an increased disposal costs of by-products and therefore the need for searching applications in different fields like feeds and pet foods, energy, fertilizers, chemicals and pharmaceuticals, trying to give them added-value and compensate such costs (Toldrá, Mora, & Reig, 2016). So, technological innovations are needed, especially for category 3 by-products, to create high added-value from meat by-products with the least environmental impact as a transition to bioeconomy. The choice of technology will depend on the composition of the by-product, its amount and availability of the target substance (Strom-Andersen, 2020).

Valorization is also performed with those edible parts of the carcass, known as co-products, with potential to be used for human consumption, either directly or through further processing (Mullen et al., 2017).

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For instance, some meat co-products such as hearts, tongues, livers, kidneys, lungs and others contain relevant amounts of nutrients like vitamins, minerals and essential amino acids that make them a nutritious food or a source of valuable compounds (Aristoy & Toldrá, 2011; Honikel, 2011; Kim, 2011). Other co-products, such as the blood collected hygienically (e.g. closed loop), contain substances like proteins with technological functions that could contribute to its valorization (Toldrá & Reig, 2011; Valta et al., 2015) or bioactive substances that may be generated from co-products through enzymatic hydrolysis (Mora, Reig, & Toldrá, 2014; Adhikari, Chae, & Bressler, 2018, (Toldrá, Lynch, Couture, & Alvarez, 2019).

Meat co-products are traditionally consumed as foods or as food ingredients in many countries. Such co-products have a high nutritional value due to their content in vitamins, essential amino acids, minerals, and trace elements (Honikel, 2011). For instance, some co-products like blood or tripe are consumed as part of traditional diet and culture in many countries being valorized (Nollet & Toldrá, 2011) while they may be considered as inedible foods in other countries and therefore having much lower value. Furthermore, separated edible fats can be used as shortenings in baking, frying agent and also to enhance the flavor of foods, meat extracts which are used for broths and soups; or gelatin, obtained from collagen, that has multiple applications in a wide variety of foods (Ockerman, Basu, & Toldrá, 2017).

This manuscript reviews the latest developments in adding value to meat by-products and co-products and discussing opportunities for making meat production more sustainable.

2. Types of meat by- and co-products

Most meat by-products are generated during the slaughter of animals for human consumption but also in the course of the disposal of dead animals and during disease control measures. Meat by-products are classified into 3 categories within the European Union according to their risk to human or animal health (EC, 2009): Category 1 by-products are considered a very high risk because they include animals that could be infected with Transmissible Spongiform Encephalopathy (TSE) or killed for TSE eradication and specified risk material. These by-products must be destroyed by incineration or co-incineration, or be used as a fuel for combustion. Category 2 by-products offer a high/medium risk with products containing residues of certain substances above the allowed levels or with presence of foreign bodies, dead animals, manure and digestive tract content. Its products are used for fuel, biodiesel, biogas, fertilizers or soil improvers. Anaerobic digestion is a well-known technology that is able to degrade solid organic waste and generate biogas, a mix of methane and carbon dioxide. In addition, anaerobic fermentation can destroy pathogens and the resulting solid product can be used as fertiliser in land applications (Escudero et al., 2014). Category 3 by-products offer the lowest risk with products such as carcasses and parts of animals slaughtered which are fit for human consumption although for commercial reasons they are not finally destined to human consumption, or rejected as unfit for human consumption even though they do not show any signs of disease communicable to humans or animals. They also include bones, hides, skins, horns and feet, and blood from ruminants and non-ruminants requiring TSE testing.

The rendering industry collects the non-edible parts of slaughtered animals and processes them through heat/pressure treatments to obtain higher value products by separating protein materials from fats. Rendering may be performed through wet or dry processing. In wet rendering, the fat is just melted so that after decantation, both the fat and the meal still contain water requiring further evaporation. In dry processing, heating conditions are more intense so that no further water evaporation is required (Woodgate & van der Veen, 2004). Typical conditions for rendering include an intense heat treatment above 133 °C with an applied pressure of 3 bars and during 20 min (EC, 2009). During rendering, animal materials are sterilized by heating and stabilized to prevent any further decomposition of products during storage. In this way, the product is evaporated, about 65% by weight corresponds to removed water, and sterilized. After rendering, the fat and the solid protein fraction are mechanically separated and processed in different applications (Woodgate & van der Veen, 2004). The protein fraction is made into protein meal by milling. Fats are skimmed off and devoted to the oleochemical industry for the production of cosmetics, feeds, soaps and detergents, and pharmaceuticals, while increasing amounts of fats are devoted to biodiesel production (EFPRA, 2020b). In fact, new technologies have expanded the range of applications of animal by-products for the generation of energy (biodiesel), especially those from category 2 and 3 (Toldrá-Reig, Mora, & Toldrá, 2020a).

Edible rendering may be also applied to animal co-products giving edible fractions that can be used as food ingredients. They are tallow or lard and a solid protein product named greaves; and also a stick water, if bones or tissues have been rendered, that contains about 1.1 to 1.3% of proteins with interesting gelling properties. (Álvarez, Drummond, & Mullen, 2018a, 2018b). A good number of animal by-products have important uses and applications as described later (Pearl, 2014).

Blood is a fluid obtained at a very large scale, especially in porcine and bovine slaughterhouses. Amounts near 3.0–3.5% for live weight of pigs and 3.3–4.0% for cattle may be recovered. Blood, that is a mixture of plasma (up to 60%) and blood cells (about 30–40%), contains about 17–19% of proteins with high nutritional value and good functional properties that make them interesting for obtaining good profitability (Bah, El-Din, Bekhit, Carne, & McConnell, 2016). The cellular fraction contains red blood cells (erythrocytes), white blood cells (leukocytes) and platelets while plasma contains 6% to 8% proteins, consisting majorly of albumin, fibrinogen and globulin (Ofori & Hsieh, 2011). The blood from bovine must be assured for the absence of any infectivity risk like TSE and therefore only hydrolyzates below 10 kDa to assure such lack of infectivity may be used for petfoods and feeds for aquaculture (EC, 2009). If blood is hygienically collected (e.g. closed loop) and managed in approved slaughterhouses, being cooled to 3 °C or below, then it can be considered fit for human consumption and treated as a co-product.

Other co-products such as hearts, tongues, livers, kidneys, lungs and others contain relevant amounts of nutrients and therefore may be consumed as a nutritious food (Nollet & Toldrá, 2011) or may be further processed to produce valuable ingredients for foods (Toldrá, Aristoy, Mora, & Reig, 2012). Furthermore, co-products are also generated in meat processing during production processes like dry- and wet-cured meat products. Giving value to such co-products would reduce the amount of waste and therefore it would contribute to a more sustainable and profitable meat industry. In this way, brines and trimmings from cooking meat processes can be collected as a source of proteins (Mullen et al., 2017). Other co-products generated during the deboning of dry-cured ham such as bones, skin, fat and trimmings, may be safely used for various applications in a sustainable manner. For instance, skin can be consumed as fried skin tapas, fat can be used for cooking, bones can be boiled to obtain nutritional and tasty broths and ham trimmings can be consumed as snacks (Gallego, Mora, Hayes, Reig, & Toldrá, 2019; Toldrá et al., 2016).

3. Applications of proteins

3.1. Functional ingredients

Plasma proteins have well-known properties with interesting technological applications as value-added ingredients like its use for gelation, foaming and emulsification (Cofrades, Guerra, Carballo, Fernández-Martin, & Jiménez-Colmenero, 2000; Ofori & Hsieh, 2014). Plasma proteins have good gelling properties and can also bind water making them useful for an improved sliceability and texture of meat products (Parés, Toldrá, Saguer, & Carretero, 2014). In fact, plasma proteins form a heat stable gel after heating that provides a good structure to the meat product. Plasma proteins may retain water up to 1.7 times its own weight. The replacement of phosphate by plasma proteins for binding of water was assayed in phosphate free frankfurters and results were promising (Hurtado et al., 2011). Fibrinogen and globulins have high emulsion capacity while albumin has low capacity (Alvarez, Bances, Rendueles, & Díaz, 2009). Notable volumes of foam may be created using plasma proteins although they are not stable with time (Lynch, Mullen, O'Neill, & Alvarez, 2017). The antioxidant and antimicrobial activities of plasma proteins can be enhanced by enzymatic hydrolysis and be successfully used in meat emulsions and emulsion-type sausages (Jin, Choi, & Kim, 2021). Other interesting properties of plasma proteins are a good cross-linking ability and are commercially used for cold and heat set binding (Ofori & Hsieh, 2014). Examples of major applications of blood proteins are reported in Table 1.

The combined use of fibrinogen and thrombin (Fibrimex®) results in a binding ability, that depends on the pH, moisture, and temperature of the meat, that is commercially used to bind pieces of meat and produce restructured meat products. Thrombin converts fibrinogen into insoluble fibrin polymers creating a half staggered structure (protofibril) that aggregates forming fibers and generate the 3D fibrin clots (EFSA, 2015; Lennon, McDonald, Moon, Ward, & Kenny, 2010).

Blood cells proteins also have functional properties although not so marked as plasma proteins. Another relevant drawback is the dark color and imparted metallic flavor making necessary the separation of the heme group from hemoglobin (Duarte, Carvalho Simoes, & Sgarbieri, 1999). Hemoglobin and globins also have a good foaming and emulsion capacity even though decolored globin has a reduced emulsion capacity probably due to protein denaturation (Alvarez et al., 2009). Such emulsifying capacity may be preserved if globin is discolored using ion exchange chromatography (Lynch et al., 2017). Decolored globin also exhibits good technological functions as fat replacer in meat products (Viana, Silva, Delvivo, Bizzotto, & Silvestre, 2005). Globins have gelling properties although the resulting gels are softer than those obtained by using plasma proteins. They also bind good amounts of water that may be lost if NaCl is added (Bah, Bekhit, Carne, & McConnell, 2013). Hemoglobin can be used as a natural colorant or color enhancer like I Red - 70 COLP® (Vepro). It needs to be stabilized with antioxidants and reducing agents to prevent oxidative browning resulting from the oxidation of iron in the heme group (Hsieh & Ofori, 2011). Cooked cured meat pigment dinitrosyl ferrohemochrome may be produced from red blood cells as an alternative to the cured pigment formed from nitrite (Ofori & Hsieh, 2014).

Table 1
Examples of reported applications of blood proteins in foods.

Blood proteins	Function	Food applications	References
Plasma proteins	Protein enrichment	Pasta	Yousif, Cranston, and Deeth (2003)
Plasma	Fat replacement	Bologna sausage	Cofrades et al. (2000)
Plasma proteins	Emulsification	Minced meats	Furlán, Padilla, and Campderrós (2010)
Thrombin/ fibrinogen	Binding through fibers	Restructured meat and fish	Lennon et al. (2010)
Porcine hemoglobin	Color enhancer	Sausages	Ofori and Hsieh (2011)
Heme iron polypeptides	Iron absorption	Hydrolyzates	In, Chae, and Oh (2002), Nissenson et al. (2003)
Whole blood	Black color	Blood sausage ("morcilla")	Nollet and Toldrá (2011)
Globin	Emulsification	Meat products	Ofori and Hsieh (2014)
Globin	Gelification	Meat products	Bah et al. (2013)
Globin	Fat replacement	Meat products	Viana et al. (2005)
Serum concentrate	Boost immune system	Bars and drinks	Ofori and Hsieh (2014)
Serum protein isolate	Dietary supplement	Sport bars	Ofori and Hsieh (2014)
Fibrinogen and demineralized plasma	Emulsification, foaming	Ice cream	Lynch et al. (2017)

Beef lung powder with a protein content of 87% and iron content of 1 mg/g was proposed as an ingredient for fresh pasta to improve its functional value (Jayawardena, Morton, Brennan et al., 2019). Proteins extracted from bovine lungs were subjected to treatment with cold plasma to evaluate any effects on functionality. Significant eddects were reported, especially in a decreased solubility of proteins but with an improved oil holding capacity (Pérez-Andrés, Alvarez, Cullen et al., 2019). Soluble and insoluble protein extracts obtained from porcine spleen were successfully used as functional ingredients in Frankfurt-type sausages (Toldrà, Parés, Saguer, & Carretero, 2020). The only limitation was the color provided by the soluble protein extract due to the myoglobin content. Collagen from bones is the basis of products with emulsifying properties and strong gel forming capacity like Valocoll (Sonac) or high water binding capacity and increased viscosity like BP85 (Sonac). Gelatin is obtained from collagen in skin, hide splits and bones and has many uses in food as stabilizer, thickener and texturizer (Ahmad et al., 2017). The obtention of gelatin from bones is quite complicated and recently, an acid pretreatment of bones followed by hydrolysis with pepsin at 70 °C was proposed for a better gelatin yield (Cao, Wang, Xing, Zhang, & Zhou, 2020). Other authors assayed a lipase pretreatment before the enzymatic hydrolysis of bones that facilitated the action of proteases and resulted in an increase of 2 times the degree of hydrolysis (Yao, Wang, Liu, Han, & Liu, 2020).

3.2. *Protein hydrolyzates: bioactive peptides*

Proteins from meat co-products are hydrolyzed with proteolytic enzymes under controlled conditions to generate bioactive peptides. Scientific substantiation of the efficacy and safety of bioactive peptides must be proved, especially supported with human studies, in order to have regulatory approval. The regulatory policies in several major countries are reported elsewhere (Chalamaiaha, Uluga, Honga, & Wu, 2019). There are many commercial enzymes available for protein hydrolysis such as pepsin, trypsin, chymotrypsin, corolase PP, papain and also from microbial origin like Neutrase® from *Bacillus amyloliquefaciens*, and Alcalase® from *Bacillus licheniformis* (Ryder, El-Din Bekhit, McConnell, & Carne, 2016; Toldrá, Reig, Aristoy, & Mora, 2018). Their main characteristics and conditions of use are reported in Table 2 and the flow diagram for the generation of the hydrolysate rich in peptides is shown in Fig. 1. The enzymes act as endopeptidases releasing large protein fragments, polypeptides, and peptides but may also act as exopeptidases, releasing small peptides and free amino acids from the N and C terminals (Toldrá, Gallego, Reig, Aristoy, & Mora, 2020). In most cases, the cost of separation of peptides must be reduced by using energy efficient approaches such as the electrodialysis with ultrafiltration membrane (Przybylski et al., 2020).

Peptides with sequences between 2 and 20 amino acids are those giving typical bioactivity and therefore low molecular weight extracts are prepared from hydrolyzates in order to obtain better bioactivity (Hong, Fan, Chalamaiah, & Wu, 2019). Major bioactivities are antihypertensive, antioxidant, antithrombotic, and antimicrobial, among others. ACE-inhibitory peptides usually have short sequences, between 2 and 12 amino acids, and contain some hydrophobic amino acid residues (Mora, Toldrá-Reig, & Toldrá, 2020). They are especially active if having proline, phenylalanine or other aromatic amino acids located at closest positions of the C-terminal (Ambigaipalan, Al-Khalifa, & Shahidi, 2015). Numerous ACE inhibitory peptides with IC_{50} below 10 μM have been reported after the hydrolysis of hemoglobin and plasma with pepsin, alcalase and flavorzyme (Deng, Zheng, Zhang, Wang, & Kan, 2014; Mora, Toldrá-Reig, Reig, & Toldrá, 2019) and also from gelatin hydrolyzed with thermolysin (Dierckx & Smagghe, 2011; Herregods et al., 2011). Bioactive peptides were extracted from dry-cured ham bones, that are traditionally used in stews and broths in Mediterranean countries, and assayed

Table 2
Main characteristics and conditions of use of enzymes typically used for protein hydrolysis of meat by-products. Reproduced from Mora et al. (2014) with permission of Elsevier.

Enzyme name	EC number	Temperature[a]	pH[a]	Type		Origin
Papain	3.4.22.2	60–70 °C	pH 6–7	Cysteine protease	*exo*- and *endo*-peptidase	Papaya fruit
Bromelain	3.4.22.32	35–45 °C	pH 7	Sulfhydryl protease	exo- and endo-peptidase	Pineapple fruit
Thermolysin	3.4.24.27	65–85 °C	pH 5–8.5	Metalloprotease	exo-peptidase	*Bacillus thermoproteolyticus*
Pronase	3.4.24.4	40–60 °C	pH 7.5	non-specific protease	exo- and endo-peptidase	*Streptomyces griseus*
Proteinase K	3.4.21.64	37 to 50–60 °C	pH 4–12	Serine protease	exo- and endo-peptidase	*Engyodontium album*
Neutrase	3.4.24.28	50 °C	pH 7	Metalloproteinase	endo-peptidase	*Bacillus amyloliquefaciens*
Alcalase	3.4.21.62	50 °C	pH 8	Serine proteinase	endo-peptidase	*Bacillus licheniformis*
Crude enzyme extract		40 °C	pH 8	non-specific proteases	exo- and endo-peptidase	*Raja clavata*

a- Optimum conditions for activity.

for ACE inhibitory activity, endothelin-converting enzyme inhibitory activity, platelet-activating factor-acetylhydrolase inhibitory activity, dipeptidyl peptidase-IV and antioxidant activity. Such peptides were reported to keep good stability after cooking and *in vitro* digestion demonstrating that bones from dry-cured hams may contribute positively to cardiovascular health of consumers (Gallego, Mora, Hayes, et al., 2019; Gallego, Mora, Hayes, Reig, & Toldrá, 2017).

Antioxidant peptides typically contain hydrophobic amino acids and either histidine, phenylalanine, tryptophan or tyrosine residues in their structure (Mora et al., 2014). Such peptides have been reported from lung (O'Sullivan, Lafarga, Hayes, & O'Brien, 2017) and liver (Yu, Hsu, Chang, & Tan, 2017) among others. For instance, ABTS radical scavenging activity was 86.8% when porcine liver was hydrolyzed with trypsin, while values were lower than 75% when hydrolyzed with alcalase or papain (Verma, Chatli, Kumar, & Mehta, 2017). On the other hand, similar DPPH radical scavenging activity were reported for porcine liver hydrolyzed with alcalase and papain, 42% and 37%, respectively (Yu et al., 2017).

Antimicrobial peptides have longer sequences and they act against microorganisms by forming channels or pores within the microbial membrane (Castellano et al., 2016). Numerous antimicrobial peptides have been reported from hemoglobin and plasma proteins (Borrajo et al., 2019) but also from other meat by-products like porcine liver (Verma et al., 2017). Antimicrobial peptides with sequences KYR and RYH were reported from hemoglobin hydrolyzed with pepsin (Catiau et al., 2011; Catiau et al., 2011). Other peptides like SHSLL, KLLSHSL and LLHHSL were effective against *Listeria innocua*, *E. coli*, and *S. aureus* (Adje, Balti, Kouach, Dhulster, & Guillochon, 2011).

3.3. *Protein hydrolyzates: Taste enhacers*

The use of protein hydrolyzates from meat co-products has also been recently considered as a potential source of taste and taste-enhancing peptides (see Fig. 1). In this regards, small peptides contribute to bitter, sweet and umami tastes while salty and sour tastes are related to the charge or amino acid side chains of the peptides (Iwaniak, Minkiewicz, Darewicz, & Hrynkiewicz, 2016). Some dipeptides derived from arginine amino acid such as Arg-Pro, Arg-Ala, Ala-Arg, Arg-Gly, Arg-Ser, Arg-Val, Val-Arg y Arg-Met have showed the enhancement of salty taste in fish hydrolysates (Schindler, Dunkel, Stahler, et al., 2011). Also the acidic amino acid Asp, and several dipeptides and tripeptides such as Asp-Asp, Asp-Glu, Glu-Asp, Glu-Glu, Asp-Glu-Glu and Asp-Glu-Ser derived from pork meat proteins have been reported to give this sensory property (Kęska & Stadnik, 2017). On the other hand, peptides containing the hydrophobic amino acids Ala, Pro, and Val, and/or the hydrophilic residues Lys and Gly, such as peptides Ala-Ala, Glu-Val, Ala-Ala-Ala, Ala-Gly-Ala, and Gly-Ala-Gly have been reported to give sweet taste in pork meat products (Kęska & Stadnik, 2017). Also it has been established correlations between the dipeptides Ile-Gln, Pro-Lys, Ile-Glu, Thr-Phe y Leu-Gln and changes in sweet taste in soy saurce (Yamamoto et al., 2014). Other dipeptides such as β-Ala-His and β-Ala-Gly have been identified in chicken broth and characterized as responsible for acid and meaty flavors (Dunkel & Hofmann, 2009) and showing bitter taste in Japanese food (Maehashi & Huang, 2009). In this respect, protein hydrolysis is commonly associated to bitterness due to the generation of peptides containing branched side chain and hydrophobic amino acids such as leucine, isoleucine, valine, phenylalanine and tyrosine, and some neutral amino acids with aromatic or basic residues (Maehashi & Huang, 2009).

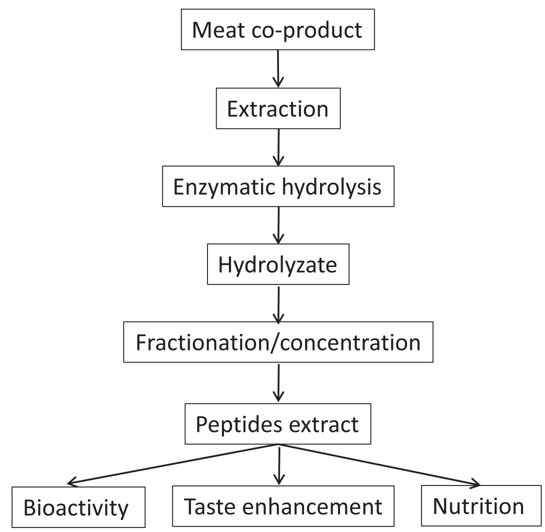

Fig. 1. Flow diagram of the enzymatic hydrolysis of meat co-products for the generation of nutritional, bioactive or taste enhancing peptides extracts.

On the other hand, it has been reported that umami has a great synergistic taste effect, as umami peptides show the taste but also are able to enhance other tastes of foods (Dang, Gao, Xie, Wu, & Ma, 2014). It was reported that α-glutamyl dipeptides with hydrophilic amino acids such as Glu-Asp, Glu-Thr, Glu-Ser, Asp-Asp, Glu-Asp, Lys-Gly, and Glu-Glu-Glu tripeptide exert umami taste at neutral pH (Tamura et al., 1989). More recently, numerous di- and tripeptides have been evaluated for their umami taste (Zhang, Venkitasamy, Pan, Liu, & Zhao, 2017). Interactions between peptides have also been investigated, discovering that certain umami tripeptides could interact and mask bitter taste via bitter taste receptors (Kim, Son, Kim, MIsaka, & Rhyu, 2015). The sequence of sensory peptides does not always include amino acids responsible for the specific taste sensation and threfore certain dipeptides could show salty taste even if they do not have in their sequence any salty amino acid. Peptides have unique taste properties that have not been observed for free amino acids like being sour and sweet suppressors, and salty and umami enhancers. Some examples are dipeptide Glu-Glu described as both bitter and sweet suppressor, Arg-Gly as salty enhancer and Pro-Glu as umami enhancer (Gallego, Mora, & Toldrá, 2019).

Regarding co-products hydrolysates, it is very frequent to obtain bitter unpleasant taste in organs hydrolysates due to the characteristics of the peptides generated. This is very challenging especially when the objective is the use of the hydrolysates as food or feed ingredients. However, there are different strategies to reduce the significance of bitter taste such as the use of exopeptidase treatments or the glycation of protein hydrolysates by Maillard reaction (Fu et al., 2020). Enzyme mixtures such as Protease A, a mixture of *endo-* and *exo*-peptidases, were assayed to generate hydrolyzates from bovine muscle and porcine plasma and resulted in low bitterness (Fu, Liu, Hansen, Bredie, & Lametsch, 2018). Another alternative was to catalyze the formation of kokumi taste via γ-glutamyl dipeptides generated through the use of γ-glutamyltranspeptidase from *Bacillus amyloliquefaciens* (Li et al., 2020).

3.4. Protein hydrolyzates for pet foods and feeds

Dry petfood contains cereals and processed animal protein that is a co-product of the meat processing industry. About 1.67 million tons of processed animal protein is destined to pet foods and 99,000 tons for fish feed (EFPRA, 2020c). Such material must proceed from animals subjected to veterinary inspection. The use of processed animal protein in feeds for any farm animals destined to food was banned (EC, 2002) and some amendments were later adopted (EC, 2009) but, in any case, high-risk material is completely forbidden for feeding farm animals. Hydrolyzed proteins produced within the European Union from meat by-products must not exceed 10.000 Da of size according to the EU Regulation (EC, 2009) and may be intended as feed for aquaculture and pet foods. Such hydrolyzates, produced as shown in Fig. 1, are rich in all essential amino acids and have the advantage of the absence of anti-nutritional factors or allergenic proteins in comparison to soybean meal (Martínez-Alvarez, Chamorro, & Brenes, 2015). Furthermore, such hydrolyzates contain small peptides that are readily absorbed in the small intestine without the need of much gastrointestinal digestion, promoting animal growth and development (Martínez-Alvarez et al., 2015).

Protein hydrolysates from meat co-products are also used as taste enhancers, as discussed in Section 3.3., for improving the palatability of those pet foods that are less palatable. Some peptides may act as palatants that stimulate the sense of taste and obtain a selective response by the animal (Araujo & Milgram, 2004). Most research has been done on the influence of each group of molecules contributing to taste separately but studies on the potential interactions between groups are scarce. So, several tripeptides having umami taste were reported to interact and mask bitter taste via bitter taste receptors (Kim et al., 2015).

The meat fraction derived from packaged food waste was used to produce pet food. Environmental benefits were observed when compared to traditional processes, with a 56.4% reduction in GWP, 22.6% less water consumption, 87.5% less land use and 21.8% reduction in fossil resource scarcity (Mosna, Bottani, Vignali, & Montanari, 2021).

There are companies producing food and petfood ingredients from blood-derived co-products and more innovative technologies are under research for an increased utilization of blood (Toldrá et al., 2019). As an example, hemoglobin has been studied as an alternative to fish meal in aqua feed. Another commercial product obtained from plasma is Palapro 80P® (Sonac) that includes immunoglobulins and hydrolyzed intestinal mucosa as feed for pigs with improved palatability and digestibility.

3.5. Bioplastics

The development of new biodegradable plastics that can constitute an alternative to petroleum-based plastics is an attractive application. This is the case of thermoplastics that are based on proteins from meat by-products. Proteins need to be concentrated and isolated which is costly but those present in blood meal and meat and bone meal are enough concentrated for such purpose (Bier, Verbeek, & Lay, 2013a, 2013b). The protein-based plastics are formed through hydrolysis of by-products proteins and extraction and modification of the hydrolyzates by chemical crosslinking through hydrogen bonding, electrostatic forces, hydrophobic bonding and disulfide cross-linking (Mekonnen, Mussone, El-Thaher, Choi, & Bressler, 2013). The intermolecular interactions between protein chains may be too extensive and, as a result, the protein-based films and coatings may be excessively brittle due to moisture desorption from the material, and would need to be formulated with specific modifiers. So, the brittleness may be reduced by adding plasticizers that also improve process-ability and modify the properties of the final structure (Bier et al., 2013a; Mekonnen, Mussone, Khalil, & Bressler, 2013). The secondary structures such as beta sheets may be disrupted with denaturants that also increase chain mobility during processing (Bier et al., 2013a, 2013b). Such protein-based films are sensitive to humidity but they get insoluble in water if they are crosslinked with epoxy resins (Mekonnen, Mussone, El-Thaher, et al., 2013; Mekonnen, Mussone, Khalil, & Bressler, 2013). Other thermoplastics have been produced using water, urea, sodium dodecyl sulfate, sodium sulfite, and triethylene glicol. The resulting dark brown color was overcome with a 4% solution of peracetic acid that could degrade heme with more luminosity and whiteness (Verbeek, Low, Lay, & Hicks, 2018).

Gelatin obtained from porcine or bovine sources may be used as renewable and biodegradable polymer to develop food packaging materials at low cost. Gelatin coating has been applied to meat products in order to extend its quality and shelf-life. Such coating reduces purge, color loss, and aroma deterioration because gelatin acts as a barrier to water and oxygen (Jridi et al., 2018). Some active compounds like natural antioxidants, extracts based on phenolic compounds, and antimicrobials like essential oils, may be added to gelatin and polymers formulations obtaining active films that can extend food shelf-life and therefore contribute to reduce food waste (Etxabide, Uranga, Guerrero, & de la Caba, 2017). Gelatin was recently enriched with an hydrolysate of tomato by-products with high antioxidant activity and applied as pork meat coating. The antioxidant activity was reported to be stable to cooking and therefore the lipid oxidation was retarded and the shelf-life was extended (Gallego, Arnal, Talens, Toldrá, & Mora, 2020).

3.6. Pharmaceutical applications

Plasma proteins can also contribute to health. So, Immunolin® is a commercial preparation produced by EnteraHealth LLC company consisting of serum-derived bovine immunoglobulin protein isolate. Immunoglobulins are claimed to support the digestive tract by binding potentially toxic antigens and therefore improving the immune system (Pearce et al., 2011). An oral iron supplement is produced from the blood cells fraction like Proferrin® (Colorado BioLabs) that is an made from bovine heme iron polypeptide and is claimed to facilitate iron absorption (Nissenson et al., 2003; Lee and Song, 2009; Seligman et al., 2000).

The oral ingestion of collagen hydrolyzates have been reported to benefit joint health and alleviate osteoarthritis (Bello & Oesser, 2006). Collagen peptides contribute to reduce the destruction of osteoarthritic cartilage in knee joints with a relief of pain and increased functional capacity in osteoarthritis patients (Puigdellivol et al., 2019). Such peptides have been reported to stimulate regeneration of type II collagen and the biosynthesis of proteoglycans in cartilage tissue osteoarthritis (Zdzieblik, Oesser, Gollhofer, & König, 2017). Collagen type I obtained from skin and tendon tissues and collagen type III obtained from articular cartilages have good properties for its use as biomaterial for regenerative medicine (Thomas et al., 2016). Collagen has also many applications in cosmetics and dermatology (Avila Rodríguez, Rodríguez Barroso, & Sánchez, 2018) as well as gelatin (Djagny, Wang, & Xu, 2001; Gómez-Guillén, Giménez, López-Caballero, & Montero, 2011).

3.7. Other applications

Other emerging industrial application of animal waste proteins is as feedstock for the production of coagulants and flocculants that are processes used for waste-water treatment (Mekonnen, Mussone, & Bressler, 2016). Kaolin floculant activity was reported for the soluble fraction of meat and bone meal and also for the high molecular weight of the hydrolysate obtained when treated with either trypsin or subtilisin (Piazza & García, 2014).

Protein-based wood adhesives were obtained from bovine water soluble blood meal. They showed good adhesive strength and water resistance for their use in composite wood products; however, when the proteinaceous material was hydrolysed, the adhesive strength was moderate and the water resistance poor, needing chemical crosslinking or other modfications to get improved performance (Adhikari et al., 2018).

4. Applications of fats

4.1. Foods

Edible fats separated during meat processing can be used as shortenings in baking and confectionery. Pork lard and beef tallow are used for cooking and frying and also to enhance the flavor and consistency of broths and soups (Alfaia et al., 2020).

4.2. Cosmetics, pharmaceuticals and chemicals

Fats are used in hand and body lotions, creams and bath products. Rendered fats can be used for the polymerization of rubber and plastic, and in plasticizers, lubricants and softeners (Ockerman & Basu, 2014).

4.3. Bioplastics

Polyhydroxyalkanoates (PHAs) are biodegradable polyesters that are produced from rendered animal fats of category 2 and 3 using bacteria like *Ralstonia eutropha* that can store up to 90% of its dry cell weight as PHA. Strains of *Pseudomonas* or genetically modified bacteria can be also used as biocatalyst (Riedel et al., 2015). The properties of PHAs are comparable to plastics produced from petroleum even though the production costs are much higher. PHAs are non-toxic and have good thermal stability, high protection against UV radiation, and exhibit good oxygen barrier (Riedel & Brigham, 2020). The migration behaviour showed reasonable values (Scarfato, Di Maio, & Incarnato, 2015).

4.4. Biodiesel

In recent years, fat waste has got a relevant use for the production of biodiesel (Ramos, Días, Puna, Gomes, & Bordado, 2019). This is due to the relevant advantages of biodiesel because it is biodegradable, non-toxic and has a good combustion emission profile allowing lower emissions of sulfur, carbon monoxide, particulate matter and unburned hydrocarbons (Xue, Grift, & Hansen, 2011). Furthermore, fossil diesel can be partially replaced with biodiesel up to 20%, known as B20, without the need of substantial modification in engines. Biodiesel consists of monoalkyl esters of long chain fatty acids produced from oil or fat. The process, that is shown in Fig. 2, is relatively simple and consists of transesterification of fat with a short chain alcohol and a catalyst, usually an alkaline catalyst, to yield a mixture of fatty acid methyl esters that constitute the biodiesel and glycerol which is a side product that can be recovered (Banković-Ilić, Stojković, Stamenković et al., 2014). Animal fats contain free fatty acids and water that affect the transesterification and reduce the biodiesel yield because soap may be formed. This makes necessary a pretreatment to remove the excess of water by drying or with silica gel, remove free fatty acids by neutralization and separation, and remove the suspended solids by filtration through cellulose filters (Gebremariam & Marchetti, 2018). Alternatives to pretreatment of animal fats are the use of a heterogeneous catalyst or the enzymatic hydrolysis with lipases that hydrolyze triglycerides into free fatty acids that in the presence of short chain alcohol generate the fatty acid methyl esters (Toldrá-Reig et al., 2020a). A further improvement is the immobilisation of lipases to get a better efficiency and lower costs because the enzyme is more stable and resistant to any denaturation by alcohol (Toldrá-Reig, Mora, & Toldrá, 2020b).

The European Union is the world's largest biodiesel producer with 202 plants that produced 14 million tonnes of biodiesel in 2019 (Bockey, 2019) and about 6% of total feedstock used, that is mostly vegetable fats and recycled fats from cooking, was animal fats (Flach, Lieberz, & Bolla, 2019). In the US, the amount of animal fats used for biodiesel in 2019 represented 8.4% of total feedstocks (US Energy Information Administration, 2020).

5. Applications of minerals

Phosphorus and calcium are important nutrients that are used as ingredients for pet foods and feeds, but phosphorus is also used as fertiliser. Phosphorus and calcium are produced from bones by crushing and degreasing, followed by a few days treatment with diluted hydrochloric acid and precipitation of calcium-phosphate (Grobben, Steele, Somerville, & Taylor, 2006). It can also be obtained through thermochemical processing (Bujak, 2015). Different products derived from bones and containing phosphorus and calcium are commercialized by Sonac. Dicalcium phosphate can be used as fertiliser but also as feed supplement offering good digestibility and improved yield of milk in dairy cows as well as good bioavailability of calcium and phosphorus for bones growth (Grobben et al., 2006). Tricalcium phosphate can be obtained from the hydroxyapatite in bones and be used as fertiliser, feed ingredient, or biomedical applications. Further, bacteria *Bacillus megaterium* was reported to solubilize phosphate from bones in order to obtain phosphate biofertilizers (Wyciszkiewicz, Saeid, Chojnacka, & Górecki, 2015). The incineration of meat and bone meal leaves ashes mainly composed of calcium phosphates such as hydroxyapatite and whitlockite (Coutand, Cyr, Deydier, Guilet, & Clastres, 2008). Such a residue rich in calcium and phosphate can be used as fertiliser with the advantage of having low content in heavy metals in comparison to mineral phosphates (Deydier, Guilet, Sarda, & Sharrock, 2005). Mechanically separated meat

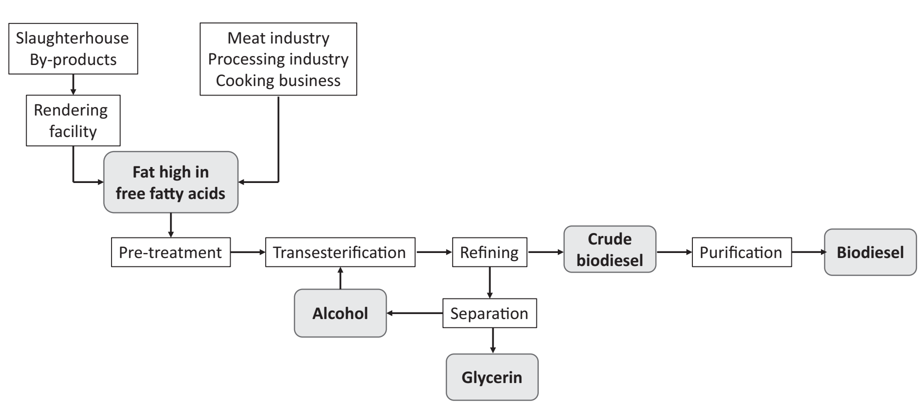

Fig. 2. Major steps in the production of biodiesel from animal fat waste. Reproduced from Toldrá-Reig et al. (2020a) with permission.

constitutes a good source of calcium and phosphorus due its content in small pieces of bones (Ockerman et al., 2017).

Liver is a good source of various micronutrients such as iron and zinc. Blood also constitutes a good source of heme iron that can be used as a supplement for those individuals with iron defficiency. Such iron absorption has been reported to be facilitated if associated to a polypeptide (Nissenson et al., 2003; Seligman et al., 2000).

6. Pharmaceuticals from other meat by/co-products

Heparin is a complex mixture of highly sulfated polysaccharides with well-known anticoagulant properties that is produced since the 1920s from animal sources (Szajek et al., 2016). It was originally produced from bovine liver but later was produced from bovine lungs and porcine mucosa being the last one the preferred for industrial production even though other countries prefer the bovine origin for religious reasons or production shortages due to large demand (Szajek et al., 2015). However, the activity of bovine heparin is significantly lower than porcine heparin (Bianchini, Liverani, Mascellani, & Parma, 1997). Most of the commercial heparin is extracted from porcine intestinal mucosa into aqueous solution. It follows a purification procedure consisting of binding to an anion exchange resin and elution with salt followed by digestion with proteases to separate heparin from the mast-cells and proteoglycans, concentration by precipitation with organic solvent or anion exchange resins, oxidation/bleaching and further solvent purification, 0.22 μm filtration, precipitation with alcohol and freeze drying (Szajek et al., 2016; Van der Meer, Kellenbach, & van den Bos, 2017).

Chondroitin sulphate is an acidic polysaccharide comprised of repeated disaccharide units of *N*-acetylgalactosamine and glucuronic acid that is present in the extracellular matrix of the cartilage and connective tissues in animal co-products such as rachea, tendons, bones, cartilage and bovine nasal septum. This substance has been reported to exert anti-inflammatory effects and also induce the production of hyaluronic acid, that improves joint mobility and pain relief in osteoarthritis, and is also used for wound healing (Sundaresan et al., 2018).

Many substances of medical interest are obtained from parathyroid, pituitary, adrenal, thyroid and thymus glands, pancreas, ovaries, and testes (Irshad & Sharma, 2015). Some of such substances are estrogens, progesterone, insulin, trypsin, parathyroid hormone, somatotropin, testosterone, thyroxin, and thymosin. Pork skin is also used as dressing for human burns and ulcers (Jayathilakan, Sultana, Radhakrishna, & Bawa, 2012).

7. Other industrial applications from meat by-products

Leather products are obtained from cattle hides. They constitute a relevant by-product representing 7–8% of the animal weight (Ockerman & Basu, 2014). So, many products like shoes, purses, handbags, belts, leather clothes, and gloves are produced worldwide.

8. Conclusions

The production of meat and meat products is characterized by an unfavorable impact on the environment, which requires rational management of these products in the entire chain from farm to fork; this implies production, processing, transport and consumer stage. Innovative solutions are being developed to create high added-value from meat processing chains with the least environmental impact. A good number of developments are already available and even in use for industrial applications in areas so varied as food, feed, pet food, pharmaceutical, chemical and energy. Future work will focus on new applications for all types of meat by- and co-products, the evaluation of the environmental impact of the new processes, especially on water and energy consumption, and the improvement of the economic profitability of the processes considering that commercialistion will depend on the market, official regulations and consumers acceptance.,

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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