Functional fermented meat products with probiotics—A review

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Abstract
Fermentation has been an important strategy in the preservation of foods. The use of starter cultures with probiotic activity has gained the attention of researchers to produce functional fermented meat products. This review aims to overview the main strengths, weaknesses, opportunities and threats of fermented meat products with probiotics. Fermented meat products can be considered as a relevant matrix for the delivery of probiotics with potential health benefits. Moreover, fermented meat products produced by traditional methods are sources of probiotics that can be explored in the production of functional meat products. However, some barriers are limit the progression with these products: the complex selection process to obtain new and tailored probiotic strains, the current perception of healthiness associated with meat and meat products, and the limited application of probiotic to fermented sausages. Promising opportunities to improve the value of functional fermented meat products have been developed by exploring new meat products as functional fermented foods, improving the protection of probiotics with microencapsulation and improving the quality of meat product (reducing nitrate and nitrate salts, adding dietary fibre, and exploring the inherent antioxidant and cardioprotective activity of meat products). Attention to potential threats is also indicated such as the unclear future changes in meat and meat products consumption due to changes in consumer preferences and the presence of competitors (dairy, fruit and vegetable-based products, for instance) in more advanced stages of development and commercialization.

Significance and Impact of Study: This review provides an overview of the Strengths, Weakness, Opportunities and Threats related to the development of functional fermented meat products with probiotics. Internal and external factors that explain the current scenario and strategies to advance the production are highlighted.

KEYWORDS
autochthonous probiotics, health benefits, healthier meat products, microencapsulation, probiotics, sausages, starter cultures
INTRODUCTION

Improving the quality and preservation of foods by microbial fermentation is an ancient strategy that has evolved to produce modern functional fermented food products (Behera & Panda, 2020). Traditionally, fermented foods have been produced using traditional practices that rely on the exposure and consequent growth of autochthonous/endogenous microorganisms that modify the composition of foods (Kumar et al., 2017). In the case of meat products, microbial growth gradually affect physicochemical, textural, sensory and functional properties of meat mass, which leads to products with appreciated colour, flavour and aroma that can be stored for long periods (Halogarda & Wójciak, 2021; Kumar et al., 2017).

Due to the modernization of the food industry and increasing knowledge about fermented meat products, the use of starter cultures became a relevant strategy to improve the control of processing and quality (Laranjo et al., 2017, 2019). Among the many current options of starter cultures for fermented meat products, the choice for microorganisms with additional health benefits have been gaining more attention among researchers due to the potential health benefits associated with these microorganisms (Bis-Souza et al., 2019; Sirini et al., 2021). Special attention has been given to the consumption of probiotics: living microorganisms that can exert health benefits when consumed in adequate amounts and modify the gut microbiome (Binda et al., 2020; FAO/WHO, 2002).

Improving the immunologic response, female reproductive health and gastrointestinal function as well as in the management of diseases such as traveller’s disease and microbial infections (especially Clostridium difficile and Helicobacter pylori) have been associated with the consumption of probiotics (Khalesi et al., 2019; McFarland et al., 2018). Moreover, other studies have been suggesting that additional benefits such as improving mental health and cognitive function, quality of life in the elderly population and in the management of diabetes can be related to the consumption of probiotics (Das et al., 2020; Kim et al., 2016a; Sivamaruthi et al., 2018). Incorporating probiotics into meat products (especially in the production of fermented meat products) is considered as one of the main strategies to produce functional meat products (meat products with potential benefits that are beyond their nutritional value) (Ojha et al., 2015). Fermented meat products with probiotics can also be seen as part of the Sustainable Development Goals of the 2030 Agenda of United Nations in the goal Good health and Well-being, particularly in strengthen the capacity of countries to reduce and improve the management of health risks by means of advancing efforts in preventive medicine and intending to reduce health care costs for the general population (Daliri & Lee, 2015; UNDP, 2021).

To the best of our knowledge, the use of strength, weakness, opportunities and threat (SWOT) analysis has not been carried out to evaluate the production, health benefits and related aspects of fermented meat products with probiotics. Thus, this review aims to provide an overview of the functional fermented meat products by means of its strengths, weakness, opportunities, and threats (Figure 1).

STRENGTHS

Fermented meat products are suitable carriers for probiotics

Using meat products as carriers of probiotics is an interesting option to produce functional fermented foods (Bis-Souza et al., 2019). The scientific evidence that support the use of fermented sausages as carriers of probiotics is supported by studies carried out in humans. For instance, the consumption of a fermented sausage containing Lactcaseibacillus paracasei (former Lactobacillus paracasei) LTH 2579 led to the successful colonization of gut environment after 3 days of consumption in health subjects (Bunte et al., 2000). A further experiment with this strain in a probiotic sausage reported a slight induction of immunological response (antibodies against oxidized LDL and CD4 (T-helper)-lymphocytes) in 20 subjects during 5 weeks (Jahreis et al., 2002).

Similarly, an experiment with Lactiplantibacillus plantarum (former Lactobacillus plantarum) MF1298 indicated that the inoculation in a sausage increased the number of individuals carrying this microorganism in relation to individuals that consumed the probiotic in capsules (Klingberg & Budde, 2006). A similar experiment indicated that consuming 25 g/day of a fermented sausage with Lactcaseibacillus rhamnosus (former Lactobacillus rhamnosus) CTC1679 for 21 days successfully modified the composition of faecal flora in human subjects (Rubio et al., 2014). Moreover, the study also revealed that the probiotic strain was detected up to 3 days after the interruption of probiotic consumption. No adverse effects were reported for the consumption of functional fermented sausages in the aforementioned studies.

Diversity of strains to produce functional fermented meat products

Due to the scientific evidence supporting the successful colonization of human intestinal flora and health benefits, other studies have been carried to search for suitable probiotic candidates. Some interesting candidates for the production of fermented meat products are Bifidobacterium longum
KACC 91563 (Song et al., 2018); Enterococcus faecium CECT 410 (Cavalheiro et al., 2021); and CRL 183 (Roselino et al., 2017); Lactcaseibacillus casei (former Lactobacillus casei) ATCC 393 (Sidira et al., 2014a) and SJRP 66 (Bis-Souza et al., 2020); L. paracasei DTA83 (Oliveira et al., 2021); L. rhamnosus LOCK900 (Neffe-Skocińska et al., 2020); L. plantarum 299v (Blaiotta et al., 2018), and CD101 (Kong et al., 2020; Yu et al., 2020), L125 (Pavlí et al., 2020); Lactobacillus acidophilus CRL1014 (Roselino et al., 2017); Lactobacillus sakét 23K (Najjari et al., 2020); Limosilactobacillus fermentum (former Lactobacillus fermentum) R6 (Sun et al., 2020); and Staphylococcus simulans NJ201 (Kong et al., 2020; Yu et al., 2020). These strains fulfill the requirements for the production of fermented meat products with probiotics and supported due to the successful colonization of meat mass and high counts throughout processing (resistance to sodium chloride and nitrate/nitrite salts) and minor effect in quality (colour, pH, oxidative status, texture properties and sensory attributes).

Enterococcus faecium CRL 183 inoculated in a salami-type sausage reduced lipid oxidation and did not affect the pH and aw in relation to control sausage (Roselino et al., 2017). Moreover, a count of around 7 log UFC/g was reported in the final product inoculated with the probiotic strain. Likewise, a high count of L. rhamnosus LOCK900 and the absence of Salmonella spp. and Listeria monocytogenes in fermented pork sausage (Neffe-Skocińska et al., 2020). The sausages produced with this probiotic microorganism also had a slight low pH and lipid oxidation values at the end of processing period in relation to noninoculated sausage. Similarly, bovine salami produced with L. plan tarum 299v had high counts in final product and during 60 days shelf life (Blaiotta et al., 2018). Additionally, the authors did not indicate significant effects in sensory attributes between control and probiotic sausages.

**Meat and meat products are natural potential sources of probiotics**

Since microorganisms have a central role in the production of functional fermented meat products, searching for potential probiotics is a strategic action to improve the number of options of starter cultures and knowledge about probiotics in functional meat products (Leroy et al., 2006). In this line of thought, many studies have been...
carried out to characterize the autochthonous probiotics isolated from meat and traditionally/naturally fermented meat products (Munekata et al., 2020). The selection of autochthonous microorganisms follows the recommendations found in the scientific literature for the selection of probiotics by characterizing the safety and potential use as starter culture in fermented meat products, to prevail digestion process and to colonize the intestinal environment (FAO/WHO, 2002).

Some potential probiotics (characterized in vitro) for application in fermented meat products are the strains Lactobacillus lactis CTC 204 and L. plantarum CTC 368 isolated from fresh meat, cooked and fermented meat products (Moreno et al., 2018); L. plantarum CB9 and CB10 strains obtained cured beef (Wang et al., 2018); and E. faecium MZF1, MZF2, MZF3, MZF4 and MZF5 naturally present in Dried Osban, a traditional Tunisian fermented meat product (Zommiti et al., 2018).

In a similar way, Staphylococcus sp. DBOCP6 was indicated as a probiotic naturally found in an Indian fermented meat (Borah et al., 2016). The traditional Turkish sausage Sucuk can also be considered as a natural source of probiotics (Yuksekdağ & Aslim, 2010). In this case, the Pediococcus pentosaceus Z12P and Z13P strains were selected among the isolates (P. pentosaceus Z9P, Z12P and Z13P, Pediococcus acidilactici Z10P, and Pediococcus dextrinicus Z11P).

**Probiotics used as starter cultures in fermented meat products have potential to induce health benefits**

The health benefits of functional fermented meat products with probiotics is mainly supported by studies that evaluated the biological effects at human level (Bunte et al., 2000; Jahreis et al., 2002; Klingberg & Budde, 2006; Rubio et al., 2014). In addition to these studies, other studies with probiotic candidates support the role of functional fermented meat products by combining the scientific evidence of studies carried in food science (probiotics used as starter cultures) and medicine areas (probiotic tested for health benefits in animals and humans) (Table 1). In these studies, the effect of matrix (meat products) at biological level is not known but the health benefit derived from probiotic exposure/consumption is evaluated in detail by administering them orally, adding to feeding or consuming as capsules. An example is a study carried out with B. longum KACC 91563 as starter culture in a fermented sausage (Song et al., 2018). An addition experiment in mice splenocytes and macrophages indicated that B. longum KACC 91563 induced an immunologic response (Park et al., 2019).

Other health benefits associated with selected probiotics used in the production of fermented meat products were reported in vivo (mice, rabbits, and piglets) for B. longum KACC 91563 in the reduction of immunological response to consumption of ovalbumin (Kim et al., 2016b), E. faecium CRL 183 to ameliorate the formation of tumours and aberrant crypt foci (Sivieri et al., 2008), E. faecium CECT 410 in the colonization of pig gut microbiome and reducing the coliform counts in faeces (Guerra et al., 2007), and E. faecium CRL 183 to reduce the impact of high-cholesterol diet in rabbits (Cavallini et al., 2009).

Regarding clinical trials, the regular consumption of L. plantarum 299v was associated with improved health status in patients with depression (Rudzki et al., 2019), diagnosed with cancer and under enteral nutrition (Kaźmierczak-Siedlecka et al., 2020), and in immunosuppressive and antibiotic treatment to prevent C. difficile infection (Dudzicz et al., 2018).

**WEAKNESS**

**Complex selection process to obtain new functional starter cultures**

Selecting a new probiotic starter culture to be used in the production of functional meat products is a complex, multistage, expensive, and multidisciplinary task that involves the fields of microbiology (Pereira et al., 2018; Yadav & Shukla, 2017), food science (Granato et al., 2020), and medicine (Islam, 2016). The selection process of potential probiotic is comprised of several in vitro and in vivo tests that aim to identify candidates at strain level, characterize the capacity to survive the stress caused by the digestion (resistance to low pH and gastric enzymes in the stomach, and resistance to high pH and bile salts), colonize the intestinal environment (adherence to enterocytes, auto- and co-aggregation, antimicrobial activity), be safe (absence of virulence factors, low resistance to antibiotics and no production of enterotoxins), as well as the technological aspects related to the quality and storage stability of fermented meat product (meat mass colonization, generation of expect physicochemical, textural and sensory changes) (Bis-Souza et al., 2019; FAO/WHO, 2002; Munekata et al., 2020).

Essentially, strains fulfilling all the criteria are the best candidates to be explored in the production of probiotic meat products. This consideration drastically reduces the number of potential probiotic strains among the total number of isolates in order to find the most suitable candidates. For instance, among the 169 Lactobacillus spp. strains isolated from fermented pork sausages in a recent study, only L. fermentum 3007 and 3010 strains displayed...
| Probiotic strain       | Study supporting the use as starter culture in meat product | Characteristics of the study                                                                 | Effect                                                                                      | Reference supporting health benefit |
|------------------------|------------------------------------------------------------|-----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|-------------------------------------|
| **Ex vivo**            |                                                            |                                                                                              |                                                                                              |                                     |
| *Bifidobacterium longum* KACC 91563 | (Song et al., 2018)                                        | 4 weeks old BALB/c mice splenocytes and macrophages; 6, 7 and 8 log CFU/mL                    | Reduction of T- and B-cell proliferation and immunoglobulin E biosynthesis                   | (Park et al., 2019)                |
| *B. longum* KACC 91563 | (Song et al., 2018)                                        | 6–8 weeks old BALB/c wild-type mice; intragastric gavage; 9.7 log CFU/mouse; every 3 days for 2 weeks | Induced T-mast cell apoptosis and reduced ovoalbumin symptoms (diarrhea)                    | (Kim et al., 2016b)                |
| *Enterococcus faecium* CRL 183 | (Roselino et al., 2017)                                    | 4 weeks old Wistar SPF mice; 8 log CFU/mL (3 ml/kg); intragastric gavage; 42 weeks           | Induced immunological response and reduction the incidence of tumours and aberrant crypt foci | (Sivieri et al., 2008)             |
| *E. faecium* CECT 410  | (Cavalheiro et al., 2021)                                  | 21 days old piglets; 10 log CFU/mL; in feeding; everyday for 42 days                         | Improved health status and reduced coliform count in faeces                                | (Guerra et al., 2007)              |
| *E. faecium* CRL 183   | (Roselino et al., 2017)                                    | 8–9 weeks old New Zealand white male rabbits; 8 log CFU/day; in feeding; once a day for 60 days | Increase serum HDL levels and reduced serum triglycerides levels                             | (Cavallini et al., 2009)           |
| **Human trials**       |                                                            |                                                                                              |                                                                                              |                                     |
| *Lactiplantibacillus plantarum* 299v | (Blaiotta et al., 2018)                                   | 60 subjects; 10 log CFU/capsule; two capsules per day for 4 weeks; double-blind, randomized, and placebo-controlled design | Increased cognitive performance and reduced kynurenine levels in patients with depression    | (Rudzki et al., 2019)              |
| *L. plantarum* 299v    | (Blaiotta et al., 2018)                                    | 40 subjects; 10 log CFU/capsule; two capsules per day for 12 weeks; randomized, double-blind, and placebo-controlled design | Improved health status and reduce the gastroenteric impact of enteral nutrition             | (Kaźmierczak-Siedlecka et al., 2020) |
| *L. plantarum* 299v    | (Blaiotta et al., 2018)                                    | 277 subjects; 10 log CFU/capsule; one capsules per day for 1 year; crossover design          | Reduced the incidence of *Clostridium difficile* infection in patients on antibiotics therapy and receiving immunosuppressive drugs | (Dudzicz et al., 2018)             |
potential to be used in further experiments as probiotics (Klayraung et al., 2008). A similar experiment with isolates with *E. faecium* strains found in Sokobanja sausage (a traditional Serbian sausage), indicated that only sk7-5, sk7-8 and sk9-15 strains could be considered as probiotic candidates (Petrović et al., 2020). The evaluation of 42 isolates from *Clauscaslo* salami (traditional Italian fermented sausage) indicated that the potential probiotic were the *P. pentosaceus* 62781-3, 46035-1 and 46035-4, and *Leuconostoc mesenteroides* 14324-8 strains (Federici et al., 2014). It is relevant to mention that the concerns about the selection of probiotics are not limited to meat products and must be considered for other sources (such as dairy of cereal-based foods).

The characterization of microbial species at strain level is another factor that have been considered of great importance in the selection of starter cultures for the production of fermented functional foods (FAO/WHO, 2002; Yadav & Shukla, 2017). This concern is related to the presence of genes involved in the expression of virulence factors, antibiotic resistance, and production of toxic compounds such as biogenic amine and enterotoxins among potential candidates (Ben Braïek & Smaoui, 2019). An example of this concern can be observed in the selection of probiotic candidates from camel milk samples wherein two strains displayed β-haemolytic activity (Abushelaibi et al., 2017).

Currently, the genotypic identification are widely applied to characterize the potential probiotic strains, which comprise the 16S rRNA Sequencing and Random amplified polymorphic DNA polymerase chain reaction (RAPD-PCR) methods, which are also considered expensive in relation to traditional identification assays (Arora & Baldi, 2017; Settanni & Corsetti, 2007; Yadav & Shukla, 2017). This level of identification has been reported to identify, *L. plantarum* CD101 isolated from traditional Chinese fermented sausages (Cao et al., 2019), *L. plantarum* L125 obtained from Greek fermented sausage (Pavli et al., 2016), *L. sakei* 23K isolated from Turkey sausages (Najjari et al., 2008), and *P. pentosaceus* R1 isolated from Harbin sausages (Han et al., 2017).

In terms of technological aspects considered for the use as starter culture (especially for lactic acid bacteria [LAB]), the capacity to tolerate low pH (exposure to lactic acid), different processing temperatures, sodium chloride, and nitrite anion, as well as the necessary enzymatic activity to affect lipids and proteins (lipolysis and proteolysis, respectively) can be cited (Cruxen et al., 2019). An example of this aspect in selection of probiotics is the study carried out with *L. plantarum* CD101 (Cao et al., 2019).

It is also worth to mention that the selection of staphylococci isolates as probiotic candidates also take into account the nitrate reductase activity, since these species are directly involved in the conversion of nitrate anions into its active form nitrite anions (Kumar et al., 2017). This aspect was reported in the selection of coagulase negative staphylococci naturally found in traditional Chinese fermented sausages (Sun et al., 2019). In this case, the isolated identified as *S. simulans* NJ201 was indicated as potential probiotic.

The evaluation shelf life in fermented meat products is a process that last for long periods (ranging from several weeks to few months of ripening). Fermented meat products are obtained after long periods of ripening and are evaluated by many tests that consider the physicochemical characteristics (colour, pH, acidification rate, and water activity), texture profile (hardness, cohesiveness, and chewiness, for instance) oxidative stability, and sensory attributes during processing and in the final product (Bis-Souza et al., 2020; Blaiotta et al., 2018; Sidira et al., 2014a). Healthiness of meat products

Meat products have been traditionally seen as important sources of nutrients such as protein, fat, minerals and vitamins (Bohrrer, 2017). However, recent scientific evidence has been suggesting that the regular consumption of meat products is associated with the development of diseases such as cardiovascular illness and cancer (WHO, 2020a, 2020b, 2020c). Since meat products are produced with meat, animal fat, ingredients and additives, seems reasonable to consider that some of these components may be involved in the increased health risk (especially sodium chloride, fat, and nitrate/nitrite salts).

The most common ingredient used in the production of fermented meat products is sodium chloride that exert an important role in quality (solubilization of myofibrillar proteins and saltiness) and safety (reduction of water activity with consequent microbial growth inhibition) (Fraqueza et al., 2021; Inguglia et al., 2017; Pateiro et al., 2021). The regular consumption of sodium chloride above the daily recommendation of World Health Organization (3 g sodium or 5 g of sodium chloride) is associated with an increased risk of cardiovascular disease (WHO, 2020a). Sausages may contain between 230 and 3300 mg sodium/100 g, which indicate these meat products as important dietary sources of sodium (Allemandi et al., 2015; Webster et al., 2010).

A similar scenario has been generated about dietary fat in meat products. Animal fat has an important role in the quality and shelf life of meat products, especially fermented and dry-cured products. Improving texture, favouring the development of characteristic flavour and aroma, and influencing the oxidative stability during
processing and storage of meat products are some of the main aspects attribute to fat in meat products (Domínguez et al., 2021; Kumar, 2021). The health concern about animal fat is related to the fat content and composition: should not exceed 10% of total energy intake and have the lowest content of saturated fat content as possible (WHO, 2020b). In the case of sausages, the total fat content can be range from 10 to 20 g/100 g and around 50% of total fat can be composed of saturated fat (Cunningham et al., 2015; Matthews et al., 2003).

Other important additives used in the processing of fermented meat products are nitrate and nitrite salts. These components (in the form of residual nitrite) play an important role in the development of sensory attributes (characteristic dark red colour and cured flavour), oxidative stability (inhibition of lipid oxidation), and safety (inhibition of pathogenic microorganisms, especially the spores of Clostridium botulinum) of fermented sausages (Munekata et al., 2021). Although the use of nitrate/nitrite salts is necessary for the production of sausages, increasing evidence accumulated during the last decades has been suggesting a controversial relation between residual nitrite consumption and cancer development (Crowe et al., 2019; Dellavalle et al., 2014). Moreover, the World Health Organization have included processed meat products in the same category of tobacco and asbestos in terms of carcinogenic potential in a recent publication (WHO, 2020c).

Consumers are also another element of this context. Recent studies revealed that meat consumers are in favour of meat products reformulation involving the reduction of salt and fat, which has also been associated with increased purchase intention among frequent meat product consumers (Shan et al., 2017a, 2017b). Moreover, health-oriented reformulations have a positive impact on the perception of healthiness of meat products among these consumers (Shan et al., 2017b).

An important aspect reported in a recent study is the importance of aiming for specific shares of the meat products market. The reformulation of meat products consumed more frequently are perceived as the most accepted for reformulation. The justification for this statement is derived from the perception that improving these foods would lead to a major benefit for public health among meat products consumers (Shan et al., 2017a). This study also indicated that consumers support the reduction of salt and fat contents but are uncertain about reinforcements in meat products for children. Additionally, consumers were not prone to consume reformulated specialty-type (such as Parma ham, liver pate, salami, chorizo and pepperoni) since the consumption of these products are associated with enjoyment and any change in the formulation would change sensory attributes.

Another recent study also indicated that positive perceptions were obtained from consumers for the replacement of commercial nitrite salts (curing agents) by natural extracts (perceived as ‘natural’ and ‘healthy’) (Hung et al., 2016). In this sense, seems reasonable to indicate that the perception of healthiness of meat products and the purchase intention of their reformulated versions (salt and fat reduction and nitrite replacement) can be affected considering the target market. Consequently, an improvement towards the production of healthier meat products to meet the recommendations of health authorities and current regulations enforcing the salt and fat reduction in meat products can be achieved.

However, more effort is still necessary to increase the knowledge and develop strategies to solve current challenges about the acceptance and related purchase intention of enriched/functional meat products. This statement is derived from a recent study that reported heterogeneous responses about acceptance and uncertainty about the purchase of enriched/functional (omega 3 were preferred over vitamin E for meat product enrichment) meat products (Shan et al., 2017c). To the best of our knowledge, the consumer perception about the inclusion of probiotics in meat products remains unclear.

It is also important to mention that the perception of healthiness is also related to the perception of the health benefit, value, consumer believes and level of scepticism. Additionally, seems unlikely that consumers counteract negative health factors with positive (Shan et al., 2017b). In other words, adding a health component does not compensate for already present negative attributes of meat products. In this sense, seems reasonable to consider that aiming to reduce characteristics perceived as negative prior to adding a health component (such as probiotics) is an important step to favour acceptance and the development of enriched/functional meat products. Additionally, Shan et al. (2017b) also argued that reducing negative health aspects is also a necessary action to favour the use of health and nutritional claims in labels. In this sense, a complex scenario involving consumers’ preferences, health-related agencies and organizations, physicians, nutritionist, professionals in the meat industry and researchers has been generated around the meat products and their reformulation.

Scientific evidence about health benefits has been largely obtained using sausages and has current limitations

The scientific evidence around probiotics in meat products is mainly centred in clinical trial studies with fermented sausages (Bunte et al., 2000; Jahreis et al., 2002; Klingberg & Budde, 2006; Rubio et al., 2014). This aspect is explained by characteristics of the traditional processing of fermented sausages that favour microbial growth
to obtain specific physicochemical characteristics, safety and sensory attributes (Blaiotta et al., 2018; Cavalheiro et al., 2021; Roselino et al., 2017; Song et al., 2018). It is important to mention that fermented sausages are the main current option for the development of probiotic meat products. Since probiotics are generally sensible to high temperatures (>45°C), the viability of probiotics in thermally treated or cooked meat products may be reduced and limit the application in other meat products that are subjected to thermal processing and/or cooking by consumers (Terpou et al., 2019).

Moreover, current scientific evidence about the recommended dosage of probiotic in fermented sausage (in terms of recommended daily consumption, frequency of consumption or period of consumption) is unclear. To the best of our knowledge, only the study carried out by Jahreis et al. (2002) indicated a relation between dosage (50 g of probiotic sausage per day during 4 weeks with probiotic count of 8 log CFU/g) and health benefit in humans (induction of immunological response). Therefore, additional studies are necessary to clarify the recommended intake and the effect of matrix.

**OPPORTUNITIES**

**Explore other fermented meat products**

Exploring alternative meat products can be seen as a relevant strategy to increase the options of fermented meat products with probiotics for consumers. One interesting option is the production of dry-cured loins inoculated with probiotics. The development of functional dry-cured loin with probiotic was reported with *L. rhamnosus* LOCK900 as starter culture (Neffe-Skocińska et al., 2020; Okoń et al., 2017). In this meat product, the starter culture reduced pH, did not effect in water activity, and improved oxidative stability during processing and storage (at 4°C for up to 4 months). Moreover, the inoculated loins also had high counts of LAB and adequate microbiological quality (lower counts of Enterobacteriaceae, and absence of *Salmonella* spp., and *L. monocytogenes*). Regarding the sensory quality, another study of the same research group with *L. rhamnosus* LOCK900 and *Bifidobacterium animalis* subsp. *lactis* BB12 indicated that this combination of starter cultures produced fermented and dry-cured loins with acceptable sensory quality (Neffe-Skocińska et al., 2017). Another matrix explored as a potential function of starter cultures produced fermented and dry-cured loins with probiotics. The development of functional dry-cured loin with probiotic was reported with *E. faecium* CECT 410 into alginate beads did not affect the growth and protected the microorganisms during the ripening period with minimal effect in the quality of a pork fermented sausage, except for texture (probiotic sausages were harder than noninoculated samples) (Cavalheiro et al., 2021). A similar protective effect was also reported for *L. casei* ATCC 393 with boiled wheat grains in a fermented pork sausage (Sidira et al., 2014b). Moreover, this combination of protective material and probiotic was also associated with improved protection against microbial spoilage in a pork sausage (Sidira et al., 2014a).

Additionally, some studies indicated that cold smoking (room temperature to 30°C for 30 min to 3 h) seems to not drastically affect the viability of probiotics in sausages and loin (Najjari et al., 2020; Neffe-Skocińska et al., 2017, 2020).

**Microencapsulation of probiotics**

The viability of probiotics in functional fermented food is a crucial factor to obtain health benefits (Šipailienė & Petraitytė, 2018). Considering this aspect, exploring strategies (such as encapsulation) to improve the protection of probiotics during processing has an important role in the production of fermented meat products with probiotics (Cavalheiro et al., 2015). In this sense, the encapsulation of probiotics aims to obtain high efficiency of encapsulation, increase microbial viability, and also preserve the quality of meat products (Cavalheiro et al., 2015; Šipailienė & Petraitytė, 2018). Some studies provide a promising scenario for advances with this strategy. For instance, a recent experiment characterized the protective effect of different wall materials (such as lactose, glycerol, trehalose, and monosodium glutamate) with casein in the production of freeze-dried microcapsules with *L. casei* ATCC 393 (Dimitrellou et al., 2016a). Among the many options, the most efficient protective materials in casein were lactose and monosodium glutamate. Counts around 9 log CFU/g were obtained after 1 year of storage at 4°C, according to the authors.

The complex obtained from the combination of carboxymethyl chitosan, chitosan and alginate is an interesting wall material to produce microencapsulated *L. casei* ATCC 393 (Li et al., 2011). This study also indicated that, once microencapsulated, microbial loss attributed to low pH and bile salts during simulated digestion were reduced. A similar outcome was reported in a related experiment for *L. casei* ATCC 393 microencapsulated in a mixture of pea protein isolate and alginate via extrusion (Xu et al., 2016). A similar protective effect was reported for this probiotic using a spray-drier and powdered skim milk as wall material (Dimitrellou et al., 2016b).

The incorporation of encapsulated *E. faecium* CECT 410 into alginate beads did not affect the growth and protected the microorganisms during the ripening period with minimal effect in the quality of a pork fermented sausage, except for texture (probiotic sausages were harder than noninoculated samples) (Cavalheiro et al., 2021). A similar protective effect was also reported for *L. casei* ATCC 393 with boiled wheat grains in a fermented pork sausage (Sidira et al., 2014b). Moreover, this combination of protective material and probiotic was also associated with improved protection against microbial spoilage in a pork sausage (Sidira et al., 2014a).
Development of functional fermented meat products along with health-oriented reformulation

The development of functional fermented meat products using probiotics and health-oriented reformulation (especially reducing/replacing nitrate and nitrite salts) is an interesting advance beyond the current strategy to produce fermented meat products with probiotics. In this sense, a recent study explored the use of *L. paracasei* DTA-83 nitrate-reductase activity to develop a fermented pork sausage with celery extract (a natural source of nitrate) (Oliveira et al., 2021). The colour was preserved and a reduction in the growth of *Salmonella* spp. were reported between the probiotic and control (produced with sodium nitrate) sausages. However, the study also revealed a reduction in the capacity to inhibit the growth of *Clostridium perfringens* using the combination of probiotic and natural nitrate source in relation to the sausage prepared with sodium nitrate. Similarly, a recent experiment explored the effect of combining *Lactobacillus acidophilus* CRL1014 and fat reduction in a mixed (pork and beef) sausage with different levels of sodium nitrate and nitrite salts (Roselino et al., 2017). Minimal changes in physicochemical and microbiological properties were reported between inoculated and control (with sodium nitrate and nitrite and without starter culture) sausages.

Another possible option of meat products with probiotics is the development of symbiotic fermented meat products. This concept comprises the combination of prebiotics and probiotics in a food (Segura-Badilla et al., 2020). However, this advance was explored in a limited number of studies with fermented meat products. This strategic development was recently explored with Italian-type salami inoculated with *L. casei* SJRP66 and added of fructooligosaccharide with reduced fat content (Bis-Souza et al., 2020). The evaluation of the fermented products revealed a probiotic count of 8 log CFU/g and similar redness and lipid oxidation value to control sausages (produced with sodium nitrate).

Another interesting strategy to develop functional meat products consist in the exploration of bioactive peptides. These functional compounds are produced from the microbial activity and lead to antioxidant and cardioprotective effects. In the case of antioxidant activity, a recent experiment with *L. plantarum* CD101 in a fermented sausage indicated that small peptides obtained from inoculated product were associated with enhanced antioxidant activity by different *in vitro* methods (ABTS radical-scavenging and Ferric reducing antioxidant power methods) (Cao et al., 2019). A similar experiment with the same probiotic strain in fermented pork sausage indicated a significant increase in antioxidant activity using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenge test of peptides extracted from probiotic sausages (Luan et al., 2021). However, contrasting results were obtained using other antioxidant methods: no differences in ABTS radical-scavenging and hydroxyl radical scavenging activity methods and a slight reduction indicated by the ferrous ion chelating activity assay.

The generation of antioxidant peptides was also reported in fermented and dry-cured loin inoculated with *L. rhamnosus* LOCK900 alone and combined with *Bifidobacterium animalis* ssp. *lactis* BB12 (Okoń et al., 2017). This study indicated no significant difference between control (noninoculated) and sausages produced with *L. rhamnosus* LOCK900 in the ABTS radical-scavenging test. Conversely, the combination of probiotics increased the antioxidant activity of sausages in relation to control sample. Additionally, a significant increase in all treatments was reported between the first and the last day of storage (after 4 months).

A related study characterized the antioxidant activity of sausages produced with the combination of *L. plantarum* CD101 and *S. simulans* NJ201 (Yu et al., 2021). Significant increase in the antioxidant activity (evaluated by ferric reducing antioxidant power, DPPH, and ABTS radical-scavenging methods) was reported for probiotic treatments in relation to noninoculated sausages. Another experiment from the same research group reported similar effect in terms of antioxidant activity with the same strains (Kong et al., 2020). Additionally, the peptides generated during processing of sausage also displayed a potential cardioprotective effect (inhibition of angiotensin I-converting enzyme activity *in vitro*).

**THREATS**

The threats hypothesized to be considered for fermented meat products with probiotics are comprised concerns about the changes in meat consumption and the competition against other food products with probiotics already in the market. Regarding the first aspect, the main concern is the shift in consumer perception and values about the consumption of meat and meat products due to different motivations (Cheah et al., 2020). Environmental concerns about the production of meat animals is related to the degradation of the environment due to greenhouse emissions, water contamination, and affecting biodiversity to produce meat animals. Social-related aspects are also related to the attitude towards reduced meat consumption. Consumers willing to reduce their consumption of meat attribute an important value to this decision due to the perception of participation in a social group that positively values this attitude. Additionally, the perception of health
risks (please check the section Healthiness of meat products) also motivates some consumers to reduce meat and meat products consumption.

The second threat is related to the competition in the market of probiotics. The dairy industry, by means of yogurt and fermented milks, is well-positioned in the market of probiotics. This effect can be explained by the association of these dairy products with its original food (milk) and the perception of naturalness (Ávila et al., 2020). Considering these aspects for dairy products with probiotics seems reasonable to consider that contrast of values can be generated when fermented meat products are considered as carriers of probiotics, which can be seen as a threat to limit the insertion of fermented meat products with probiotics in this sector of food market.

Faster advances in other food products to be commercialized as probiotics is another threat to be considered (Dey, 2018). Meat products (except for fermented and dry-cured sausages, hams, loins, and other pieces) has to be thermally treated or cooked to be consumed (Cavalheiro et al., 2015). Conversely, probiotic fruit and vegetable products have been showing better technological, health and commercial potential to remain in the probiotic market (Dey, 2018).

CONCLUSION

Fermented meat products with probiotics (mainly fermented sausages) can be seen as relevant options for functional foods development since endogenous probiotics can generate has minimal impact on the quality and can promote health, to some extent. Some challenges remain to be tackled since the scientific evidence supporting the functional benefits of probiotic meat products is limited and has been growing at a slow pace than other food products and its perception of healthiness has been questioned. Further studies should explore and expand the knowledge about the development of fermented meat products with probiotics in healthier meat formulations and improve the understanding about the changes in meat and meat products consumption.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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REFERENCES

Abushelaibi, A., Al-Mahadin, S., El-Tarabily, K., Shah, N.P. & Ayyash, M. (2017) Characterization of potential probiotic lactic acid bacteria isolated from camel milk. Lwt—Food Science and Technology, 79, 316–325.

Allemandi, L., Tiscornia, M.V., Ponce, M., Castronuovo, L., Dunford, E. & Schoj, V. (2015) Sodium content in processed foods in Argentina: compliance with the national law. Cardiovascular Diagnosis and Therapy, 5, 197–206.

Arora, M. & Baldi, A. (2017) Selective identification and characterization of potential probiotic strains: a review on comprehensive polyphasic approach. Applied Clinical Research, Clinical Trials and Regulatory Affairs, 4, 60–76.

Ávila, B.P., da Rosa, P.P., Fernandes, T.A., Chesini, R.G., Sedrez, P.A., de Oliveira, A.P.T. et al. (2020) Analysis of the perception and behaviour of consumers regarding probiotic dairy products. International Dairy Journal, 106, 104703.

Behera, S.S. & Panda, S.K. (2020) Ethnic and industrial probiotic foods and beverages: efficacy and acceptance. Current Opinion in Food Science, 32, 29–36.

Ben Braïek, O. & Smaoui, S. (2019) Enterococci: between emerging pathogens and potential probiotics. BioMed Research International, 2019, 5938210.

Binda, S., Hill, C., Johansen, E., Obis, D., Pot, B., Sanders, M.E. et al. (2020) Criteria to qualify microorganisms as “probiotic” in foods and dietary supplements. Frontiers in Microbiology, 11, 1662.

Bis-Souza, C.V., Barba, F.J., Lorenzo, J.M., Penna, A.L.B. & Barretto, A.C.S. (2019) New strategies for the development of innovative fermented meat products: a review regarding the incorporation of probiotics and dietary fibers. Food Reviews International, 35, 467–484.

Bis-Souza, C.V., Penna, A.L.B. & da Silva Barretto, A.C. (2020) Applicability of potentially probiotic Lactobacillus casei in low-fat Italian type salami with added fructooligosaccharides: in vitro screening and technological evaluation. Meat Science, 168, 108186.

Blaiotta, G., Murru, N., Di Cerbo, A., Romano, R. & Aponte, M. (2018) Production of probiotic bovine salami using Lactobacillus plantarum 299v as adjunct. Journal of the Science of Food and Agriculture, 98, 2285–2294.

Bohrer, R.M. (2017) Review: nutrient density and nutritional value of meat products and non-meat foods high in protein. Trends in Food Science & Technology, 65, 103–112.

Borah, D., Gogoi, O., Adhikari, C. & Kakoti, B.B. (2016) Isolation and characterization of the new indigenous Staphylococcus sp. DB0CP06 as a probiotic bacterium from traditionally fermented fish and meat products of Assam state. Egyptian Journal of Basic and Applied Sciences, 3, 232–240.

Bunte, C., Hertel, C. & Hammes, W.P. (2000) Monitoring and survival of Lactobacillus paracasei LTH 2579 in food and the human intestinal tract. Systematic and Applied Microbiology, 23, 260–266.

Cao, C.C., Feng, M.Q., Sun, J., Xu, X.L. & Zhou, G.H. (2019) Screening of lactic acid bacteria with high protease activity from fermented sausages and antioxidant activity assessment of its fermented sausages. Cyta—Journal of Food, 17, 347–354.
Cavalheiro, C.P., Ruiz-Capillas, C., Herrero, A.M., Jiménez-Colmenero, F., Ragagnin de Menezes, C. & Martins Fries, L.L. (2015) Application of probiotic delivery systems in meat products. *Trends in Food Science & Technology*, 46, 120–131.

Cavalheiro, C.P., Ruiz-Capillas, C., Herrero, A.M. & Pintado, T. (2021) Dry-fermented sausages inoculated with Enterococcus faecium CECT 410 as free cells or in alginate beads. *Lebensmittel-Wissenschaft und-Technologie*, 139, 110561.

Cavallini, D.C., Bedani, R., Bomdespacho, L.Q., Vendramini, R.C. & Rossi, E.A. (2009) Effects of probiotic bacteria, isoflavones and simvastatin on lipid profile and atherosclerosis in cholesterol-fed rabbits: a randomized double-blind study. *Lipids in Health and Disease*, 8, 1–8.

Cheah, I., Sadat Shimul, A., Liang, J. & Phau, I. (2020) Drivers and barriers toward reducing meat consumption. *Appetite*, 149, 104636.

Crowe, W., Elliott, C.T. & Green, B.D. (2019) A review of the in vivo evidence investigating the role of nitrate exposure from processed meat consumption in the development of colorectal cancer. *Nutrients*, 11, 2673.

Cruzen, C.E.D.S., Funck, G.D., Haubert, L., Dannenberg, G.D.S., Marques, J.D.L., Chaves, F.C. et al. (2019) Selection of native bacterial starter culture in the production of fermented meat sausages: application potential, safety aspects, and emerging technologies. *Food Research International*, 122, 371–382.

Cunningham, J., Nguyen, V., Adorno, P. & Droulez, V. (2015) Nutrient composition of retail samples of Australian beef sausages. *Nutrients*, 7, 9602–9617.

Daliri, E.B.M. & Lee, B.H. (2015) New perspectives on probiotics in health and disease. *Food Science and Human Wellness*, 4, 56–65.

Das, G., Paramithiotis, S., Sundram Sivamaruthi, B., Wijaya, C.H., Suharta, S., Sanlier, N. et al. (2020) Traditional fermented foods with anti-aging effect: a concentric review. *Food Research International*, 134, 109269.

de Melo Pereira, G.V., de Oliveira Coelho, B., Magalhães Júnior, A.L., Thomaz-Soccol, V. & Soccol, C.R. (2018) How to select a probiotic? A review and update of methods and criteria. *Biotechnology Advances*, 36, 2060–2076.

Dellavalle, C.T., Xiao, Q., Yang, G., Shu, X.O., Aschebrook-Killfoy, B., Zheng, W. et al. (2014) Dietary nitrate and nitrite intake and risk of colorectal cancer in the Shanghai Women’s Health Study. *International Journal of Cancer*, 134, 2917–2926.

Dey, G. (2018) *Non-dairy probiotic foods: innovations and market trends*. Cham: Innovations in Technologies Fermented Food and Beverage Industries Springer, pp. 159–173.

Dimitrellou, D., Kandyli, P. & Kourkoutas, Y. (2016a) Effect of cooling rate, freeze-drying, and storage on survival of free and immobilized *Lactobacillus casei* ATCC 393. *Lwt—food Science and Technology*, 69, 468–473.

Dimitrellou, D., Kandyli, P., Petrović, T., Dimitrijević-Branković, S., Lević, S., Nedović, V. et al. (2016b) Survival of spray dried microencapsulated *Lactobacillus casei* ATCC 393 in simulated gastrointestinal conditions and fermented milk. *Lwt—food Science and Technology*, 71, 169–174.

Domínguez, R., Munekata, P.E., Pateiro, M., López-Fernández, O. & Lorenzo, J.M. (2021) Immobilization of oils using hydrogels as strategy to replace animal fats and improve the healthiness of meat products. *Current Opinion in Food Science*, 37, 135–144.

Dudzicz, S., Kujawa-Szewieczek, A., Kwiecień, K., Więcek, A. & Adamczak, M. (2018) *Lactobacillus plantarum* 299v reduces the incidence of *Clostridium difficile* infection in nephrology and transplantation ward—results of one year extended study. *Nutrients*, 10, 1574.

FAO, WHO. (2002) *Guidelines for the evaluation of probiotics in food*. London, ON, Canada: WHO Technical Report Series.

Federici, S., Ciarrocchi, F., Campana, R., Ciandirini, E., Blasi, G. & Baffone, W. (2014) Identification and functional traits of lactic acid bacteria isolated from Ciauscolo salami produced in Central Italy. *Meat Science*, 98, 575–584.

Fraqueza, M.J., Laranjo, M., Elias, M. & Patarata, L. (2021) Microbiological hazards associated with salt and nitrite reduction in cured meat products: control strategies based on antimicrobial effect of natural ingredients and protective microbiota. *Current Opinion in Food Science*, 38, 32–39.

Granato, D., Barba, F.J., Bursać Kovačević, D., Lorenzo, J.M., Cruz, A.G. & Putnik, P. (2020) Functional foods: product development, technological trends, efficacy testing, and safety. *Annual Review of Food Science and Technology*, 11, 93–118.

Guerra, N.P., Bernárdez, P.F., Méndez, J., Cachaldora, P. & Pastrana Castro, L. (2007) Production of four potentially probiotic lactic acid bacteria and their evaluation as feed additives for weaned piglets. *Animal Feed Science and Technology*, 134, 89–107.

Halagarda, M. & Wójciak, K.M. (2021) Health and safety aspects of traditional European meat products. A review. *Meat Science*, 108623. In press.

Han, Q., Kong, B., Chen, Q., Sun, F. & Zhang, H. (2017) *In vitro* comparison of probiotic properties of lactic acid bacteria isolated from Harbin dry sausages and selected probiotics. *Journal of Functional Foods*, 32, 391–400.

Hung, Y., Verbeke, W. & de Kok, T.M. (2016) Stakeholder and consumer reactions towards innovative processed meat products: insights from a qualitative study about nitrite reduction and phytochemical addition. *Food Control*, 60, 690–698.

Inguglia, E.S., Zhang, Z., Tiwari, B.K., Kerry, J.P. & Burgess, C.M. (2017) Salt reduction strategies in processed meat products—a review. *Trends in Food Science & Technology*, 59, 70–78.

Islam, S.U. (2016) Clinical uses of probiotics. *Medicine (Baltimore)*, 95, e2658.

Jahreis, G., Vogelsang, H., Kiesling, G., Schubert, R., Bunte, C. & Hannes, W.P. (2002) Influence of probiotic sausage (*Lactobacillus paracasei* DSM 9843) in cancer patients receiving home enteral nutrition—study protocol for a randomized, double-blind, and placebo-controlled trial. *Nutrition Journal*, 19, 1–8.

Khmelski, S., Bellissimo, N., Vandelanotte, C., Williams, S., Stanley, D. & Irwin, C. (2019) A review of probiotic supplementation in healthy adults: helpful or hype? *European Journal of Clinical Nutrition*, 73, 24–37.

Kim, B., Hong, V.M., Yang, J., Hyun, H., Im, J.J., Hwang, J. et al. (2016a) A review of fermented foods with beneficial effects on brain and cognitive function. *Preventive Nutrition and Food Science*, 21, 297–309.
Kim, J.H., Jeun, E.J., Hong, C.P., Kim, S.H., Jang, M.S., Lee, E.J. et al. (2016b) Extracellular vesicle-derived protein from Bifidobacterium longum alleviates food allergy through mast cell suppression. The Journal of Allergy and Clinical Immunology, 137, 507–516.e8.

Klayraung, S., Viernstein, H., Sirithunyalug, J. & Okonogi, S. (2008) Probiotic properties of lactobacilli isolated from Thai traditional food. Scientia Pharmacuetica, 76, 485–503.

Klingberg, T.D. & Budde, B.B. (2006) The survival and persistence in the human gastrointestinal tract of five potential probiotic lactobacilli consumed as freeze-dried cultures or as probiotic sausage. International Journal of Food Microbiology, 109, 157–159.

Kong, Y.-W., Feng, M.-Q. & Sun, J. (2020) Effects of Lactobacillus plantarum on antioxidative changes and bioactivities (antioxidant and anti-hypertensive activities) in fermented pork sausage. LWT, 133, 109985.

Kumar, P., Chatli, M.K., Verma, A.K., Mehta, N., Malav, O.P., Kumar, D. et al. (2017) Quality, functionality, and shelf life of fermented meat and meat products: a review. Critical Reviews in Food Science and Nutrition, 57, 2844–2856.

Kumar, Y. (2021) Development of low-fat/reduced-fat processed meat products using fat replacers and analogues. Food Reviews International, 37, 296–312.

Laranjo, M., Elias, M. & Fraqueza, M.J. (2017) The use of starter cultures in traditional meat products. Journal of Food Quality, 2017, 9546026.

Laranjo, M., Potes, M.E. & Elias, M. (2019) Role of starter cultures on the safety of fermented meat products. Frontiers in Microbiology, 10, 853.

Leroy, F., Verluyten, J. & De Vuyst, L. (2006) Functional meat starter cultures for improved sausage fermentation. International Journal of Food Microbiology, 106, 270–285.

Li, X.Y., Chen, X.G., Sun, Z.W., Park, H.J. & Cha, D.S. (2011) Preparation of alginate/chitosan/carboxymethyl chitosan complex microcapsules and application in Lactobacillus casei ATCC 393. Carbohydrate Polymers, 83, 1479–1485.

Luan, X., Feng, M. & Sun, J. (2021) Effect of Lactobacillus plantarum on antioxidative activity in fermented sausage. Food Research International, 144, 110351.

Matthews, K., Maureen, S. & Blades, M. (2003) Survey of the nutritional content of meat products on sale in Scotland from butchers’ shops and multiple retailers. Nutrition and Food Science, 33, 98–104.

McFarland, L.V., Evans, C.T. & Goldstein, E.J.C. (2018) Strain-specificity and disease-specificity of probiotic efficacy: a systematic review and meta-analysis. Frontiers in Medicine, 5, 124.

Moreno, I., Marasca, E.T.G., De Sá, P.B.Z.R., De Souza Moltinho, J., Marquezini, M.G., Alves, M.R.C. et al. (2018) Evaluation of probiotic potential of bacteriocinogenic lactic acid bacteria strains isolated from meat products. Probiotics and Antimicrobial Proteins, 10, 762–774.

Munekata, P.E.S., Pateiro, M., Dominguez, R., Santos, E.M. & Lorenzo, J.M. (2021) Cruciferous vegetables as sources of nitrate in meat products. Current Opinion in Biotechnology, 38, 1–7.

Munekata, P.E.S., Pateiro, M., Zhang, W., Dominguez, R., Xing, L., Fierro, E.M. et al. (2020) Autochthonous probiotics in meat products: selection, identification, and their use as starter culture. Microorganisms, 8, 1–20.

Najjari, A., Boumaïza, M., Jalbabiah, S., Boudabous, A. & Ouzari, H.I. (2020) Application of isolated Lactobacillus sakei and Staphylococcus xylosus strains as a probiotic starter culture during the industrial manufacture of Tunisian dry-fermented sausages. Food Sciences and Nutrition, 8, 4172–4184.

Najjari, A., Ouzari, H., Boudabous, A. & Zagorec, M. (2008) Method for reliable isolation of Lactobacillus sakei strains originating from Tunisian seafood and meat products. International Journal of Food Microbiology, 121, 342–351.

Neffe-Skocińska, K., Okoń, A., Kolożyń-Krajewska, D. & Dolatowski, Z. (2017) Amino acid profile and sensory characteristics of dry fermented pork loins produced with a mixture of probiotic starter cultures. Journal of the Science of Food and Agriculture, 97, 2953–2960.

Neffe-Skocińska, K., Okoń, A., Zielinska, D., Szymanski, P., Sionek, B. & Kolożyń-Krajewska, D. (2020) The possibility of using the probiotic starter culture Lactisacebaccilus rhamnosus LOCK900 in dry fermented pork loins and sausages produced under industrial conditions. Applied Sciences, 10, 4311.

Ojha, K.S., Kenny, J.P., Duffy, G., Beresford, T. & Tiwari, B.K. (2015) Technological advances for enhancing quality and safety of fermented meat products. Trends in Food Science & Technology, 44, 105–116.

Okoń, A., Stadnik, J. & Dolatowski, Z.J. (2017) Effect of probiotic bacteria on antiradical activity of peptides isolated from dry-cured loins. Cyta—Journal of Food, 15, 382–390.

Oliveira, W.A., Rodrigues, A.R.P., Oliveira, F.A., Oliveira, V.S., Laureano-Melo, R., Stutz, E.T.G. et al. (2021) Potentially probiotic or postbiotic pre-converted nitrite from celery produced by an axenic culture system with probiotic lacticaseibacilli strain. Meat Science, 174, 108408.

Park, M.J., Park, M.S. & Ji, G.E. (2019) Cloning and heterologous expression of the β-galactosidase gene from Bifidobacterium longum RD47 in B. Bifidum BGN4. Journal of Microbiology and Biotechnology, 29, 1717–1728.

Pateiro, M., Munekata, P.E.S., Ciudadini, A., Domínguez, R. & Lorenz, J.M. (2021) Metallic-based salt substitutes to reduce sodium content in meat products. Current Opinion in Food Sciences, 38, 21–31.

Pavl, F.G., Argyri, A.A. & Papadopoulou, O.S. (2016) Probiotic potential of lactic acid bacteria from traditional fermented dairy and meat products: assessment by in vitro tests and molecular characterization. Journal of Probiotics & Health, 04, 3.

Pavl, F.G., Argyri, A.A., Chorianopoulos, N.G., Nychas, G.J.E. & Tassou, C.C. (2020) Effect of Lactobacillus plantarum L125 strain with probiotic potential on physicochemical, microbiological and sensorial characteristics of dry-fermented sausages. LWT, 118, 108810.

Petrović, T.D.Ž., Ilić, P.D., Grujović, M., Mladenović, K.G., Kocić-Tanackov, S.D. & Comić, L.R. (2020) Assessment of safety aspect and probiotic potential of autochthonous Enterococcus faecium strains isolated from spontaneous fermented sausage. Biotechnology Letters, 42, 1513–1525.

Roselino, M.N., de Almeida, J.F., Canaan, J.M.M., Pinto, R.A., Ract, J.N.R., de Paula, A.V. et al. (2017) Safety of a low-fat fermented sausage produced with Enterococcus faecium CRL 183 and Lactobacillus acidophilus CRL1014 probiotic strain. International Food Research Journal, 24, 2694–2704.

Rubio, R., Martin, B., Aymerich, T. & Garriga, M. (2014) The potential probiotic Lactobacillus rhamnosus CTCL679 survives the passage through the gastrointestinal tract and its use as starter culture results in safe nutritionally

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enhanced fermented sausages. *International Journal of Food Microbiology*, 186, 55–60.

Rudzki, L., Ostrowska, L., Pawlak, D., Malus, A., Pawlak, K., Waszkiewicz, N. et al. (2019) Probiotic *Lactobacillus plantarum* 299v decreases kynurenine concentration and improves cognitive functions in patients with major depression: a double-blind, randomized, placebo controlled study. *Psychoneuroendocrinology*, 100, 213–222.

Segura-Badilla, O., Lazzcono-Hernández, M., Kammbar-García, A., Vera-López, O., Aguilar-Alonso, P., Ramírez-Calixto, J. et al. (2020) Use of coconut water (*Cocus nucifera* L) for the development of a symbiotic functional drink. *Heliyon*, 6, e03653.

Settanni, L. & Corsetti, A. (2007) The use of multiplex PCR to detect and differentiate food- and beverage-associated microorganisms: a review. *Journal of Microbiological Methods*, 69, 1–22.

Shan, L.C., De Brün, A., Henchion, M., Li, C., Murrin, C., Wall, P.G. & Monahan, F.J. (2017a) Consumer preferences towards healthier reformulation of a range of processed meat products reformulated to be healthier—a conjoint analysis study. *Meat Science*, 131, 82–89.

Shan, L.C., Henchion, M., De Brün, A., Murrin, C., Wall, P.G. & Monahan, F.J. (2017b) Factors that predict consumer acceptance of enriched processed meats. *Meat Science*, 133, 185–193.

Sun, J., Cao, C.-C., Feng, M.-Q., Xu, X.-L. & Zhou, G.-H. (2019) Technological and safety characterization of coagulase-negative staphylococci with high protease activity isolated from Traditional Chinese fermented sausages. *LWT*, 114, 108371.

Terpou, A., Papadaki, A., Lappa, I.K., Kachrimanidou, V., Bosnea, L.A. & Kopsahelis, N. (2019) Probiotics in food systems: significance and emerging strategies towards improved viability and delivery of enhanced beneficial value. *Nutrients*, 11, 1591.

UNDP. (2021) *Sustainable development goals*. New York, NY: United Nations Development Program.

Wang, J., Wang, J., Yang, K., Liu, M., Zhang, J., Wei, X. et al. (2018) Screening for potential probiotic from spontaneously fermented non-dairy foods based on in vitro probiotic and safety properties. *Annals of Microbiology*, 68, 803–813.

Webster, J.L., Dunford, E.K. & Neal, B.C. (2010) A systematic survey of the sodium contents of processed foods. *American Journal of Clinical Nutrition*, 91, 413–420.

WHO. (2020a) *Salt reduction*. Geneva: WHO.

WHO. (2020b) *Healthy diet*. Geneva: WHO.

WHO. (2020c) *Cancer: carcinogenicity of the consumption of red meat and processed meat*. Geneva: WHO.

Wójcik, K.M., Libera, J., Stasiak, D.M. & Kołozyn-Krajewska, D. (2017) Technological aspect of *Lactobacillus acidophilus* bauer, *Bifidobacterium animalis* BB-12 and *Lactobacillus rhamnosus* LOCK900 use in dry-fermented pork neck and sausage. *Journal of Food Processing and Preservation*, 41, e12965.

Xu, M., Gagné-Bourque, F., Dumont, M.J. & Jabaji, S. (2016) Encapsulation of *Lactobacillus casei* ATCC 393 cells and evaluation of their survival after freeze-drying, storage and under gastrointestinal conditions. *Journal of Food Engineering*, 168, 52–59.

Yadav, R. & Shukla, P. (2017) An overview of advanced technologies for selection of probiotics and their expediency: a review. *Critical Reviews in Food Science and Nutrition*, 57, 3233–3242.

Yu, D., Meng, M.Q. & Sun, J. (2021) Influence of mixed starters on the degradation of proteins and the formation of peptides with antioxidant activities in dry fermented sausages. *Food Control*, 123, 107743.

Yu, D., Feng, M.Q. & Sun, J. (2021) Salt reduction of enhanced beneficial value. *Nutrients*, 11, 1591.

Yuceskadag, Z.N. & Aslim, B. (2010) Assessment of potential probiotic and starter properties of *Pediococcus* spp. isolated from Turkish-type fermented sausages (Suckuk). *Journal of Microbiology and Biotechnology*, 20, 161–168.

Zommitti, M., Cambroneri, M., Maillot, O., Barreau, M., Sebei, K., Feuilloley, M. et al. (2018) Evaluation of probiotic properties and safety of *Enterococcus faecium* isolated from artisanal Tunisian meat ‘Dried Ossban’. *Frontiers in Microbiology*, 9, 1685.