

Reducing the Levels of Sodium, Saturated Animal Fat, and Nitrite in Dry-Cured Pork Meat Products: A Major Challenge

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Abstract

The curing of meat is a conservation technique widely used since ancient times to prolong shelf-life. It consists in exposing meat to a mixture of sodium chloride and nitrate/nitrite. Sodium chloride affects the flavor, texture and shelf-life of meat products. Animal fat mainly affects the flavor and texture, and nitrate and nitrite affect the color and flavor, and give cured meat products their typical aroma. Excessive intake of sodium has been linked to arterial hypertension and increased risk of cardiovascular diseases. Excessive intakes of saturated fatty acids in pork fat, and also of nitrite, have been identified as factors promoting some cancers. There is consequently an increasing consumer demand to reduce these ingredients in processed meat and so develop healthier cured meat products. This paper reviews how and to what extent sodium, animal fat rich in saturated fatty acids, and nitrite contents can be reduced in the production of dry-cured hams and dry-fermented sausages.

Keywords

Sodium, Saturated Fatty Acids, Nitrite, Dry-Fermented Sausage, Dry-Cured Ham

1. Introduction

Since ancient times, the widespread curing of pork products such as dry-fermented sausages and dry-cured hams has been used as a conservation method to extend the storage life of pork meat. The method consists in placing in contact whole muscles (ham) or mixtures of chopped lean meat and fat (sausage), with a salting mixture, often made up of sodium chloride (NaCl, hereafter “salt”), potassium nitrite or sodium nitrite (KNO₂ or NaNO₂, food preservatives E249 or E250, hereafter “nitrite”), and sodium nitrate or potassium nitrate (NaNO₃ or

KNO_3 , food preservatives E251 or E252, hereafter “nitrate”). The salting mixture preserves the food product from all microbiological spoilage by the barrier effect it induces through lowering water activity (a_w) [1]. It also contributes positively to the final organoleptic qualities of the dried/cured product, such as its color, texture, flavor and aroma. In the case of dry-fermented sausage the salting step is followed by a fermentation step, which causes pH to fall; ham undergoes a resting step at low temperature (2°C - 4°C), which allows homogenization of the salt. In both cases, there is then a drying and ripening step that allows the development of the typical aroma of this type of meat product. The pork dry-curing process varies according to geographical region, including within Europe [2]. In northern Europe, dried-cured pork products are made with short ripening times, are treated with only salt and nitrite, and usually undergo a smoking step. By contrast, in Mediterranean countries, the drying/ripening times are much longer, the salting mixture is composed of salt and nitrate/nitrite, and no smoking is performed. The final organoleptic and sensory qualities of dried-cured pork products therefore depend not only on the qualities of the raw materials and the ingredients or additives used in the formulation, but also on the various traditional production processes used in different parts of the world [3].

From a nutritional point of view, the consumption of dried-cured pork products should remain moderate, as their high salt and fat contents carry a large quantity of sodium (second-ranking source after cereal and bakery products), cholesterol, saturated fatty acids and calories into the diet. For example, final salt content reaches 5% in dry-fermented sausage, and fat content is usually in the range 30% - 50% [4]. In dry-cured Spanish *serrano* ham, salt content expressed relative to dry matter is between 8% and 15% at the end of drying/ripening [5]. It is clearly established that excessive consumption of sodium in the diet favors arterial hypertension and increases the risk of heart attack, osteoporosis [6] [7], gastric cancer [8], and kidney disease [9]. Numerous studies have shown that in European and Northern American countries, about 75% - 85% of sodium intake is attributable to industrially-manufactured food products and foods eaten away from the home, against 10% - 15% due to salt present naturally in foods, and table salt added at home during cooking and eating [10] [11] [12] [13]. The same early studies also indicated that by contrast, unlike the above countries, in most Asian countries, the salt added at home during cooking or from soy sauce are the main sources of sodium in the diet. Given the way salt is ingested in these countries, a public health campaign is needed to encourage Asian consumers to use less salt in their food preparation [14] [15]. For the reasons stated above, in European and Northern American countries, human health organizations have all enjoined the food industry to reduce salt levels in manufactured food products. For example, both the US National Academy of Sciences and the French Health Agency AFSSA recommend a maximum daily intake of sodium chloride of 6 g, which means reducing current consumption by about 50% in countries such as the US, Ireland and France. It is to be borne in mind that pork, beef, lamb and poultry meats naturally contain 50 - 70 mg of sodium per 100 g [16].

Excessive consumption of fat has been associated with an increased risk of obesity, cancer, high blood cholesterol and coronary diseases. Accordingly, the latest recommendations [17] advise limiting the consumption of fat so that it represents no more than 30% of calorie intake in the diet, while at the same time balancing fatty acids: saturated (less than 10%), polyunsaturated (6% - 10%, with ideally 5% - 8% of ω -6 and 1% - 2% of ω -3), mono-unsaturated (10% - 15%) and *trans*-unsaturated (less than 1%).

Human dietary concerns create an absolute need to develop dried-cured pork products with lower levels of sodium, saturated fatty acids, and nitrate/nitrite. More generally, large health benefits and medical costs savings may result from efforts to lower sodium, calorie and fat consumption in the human diet. He *et al.* [18] reported that even a modest reduction in dietary salt intake for at least four weeks caused a significant decrease in blood pressure in both normotensive and hypertensive individuals, irrespective of sex ($p < 0.001$ for hypertensive men and both normotensive and hypertensive women, and $p < 0.05$ for normotensive men) and ethnic group ($p < 0.001$ for hypertensive white and black people, $p < 0.05$ for hypertensive Asian people and normotensive white people and $p = 0.012$ for normotensive black people). For adult persons, Aburto *et al.* [19] conclude that lower sodium intake is assuredly associated with lower blood pressure and a reduced risk of stroke and fatal coronary heart disease, and also has no adverse effect on blood lipids or renal function. Using a cross-sectional simulation approach, Palar and Sturm [20] calculated that reducing the average daily sodium intake in the US adult population to the recommended value of 2.3 g could reduce cases of hypertension by 11 million and directly save \$18 billion in health care annually; coupled to moderate reductions in dietary intakes of calories (-100 kcal/day) and saturated fat (-5 g/d), these annual financial savings could range from \$60 billion to \$120 billion [21]. In 2011, Webster *et al.* [22] concluded that for most countries, one of the simplest, surest and most cost-effective ways of improving public health would be to implement an ambitious national salt reduction program. Through examples covering dry-cured ham (which represented a production of 46,737 tons in 2015 in France) and dry-fermented sausage (108,825 tons in 2015 in France), this paper reviews the main technological advances made in recent years that have favored the production of dried-cured pork products with improved nutritional value.

2. Reduction/Substitution of Sodium Chloride in Dry Pork Products

Although excessive sodium consumption is harmful to human health, it is also true that sodium remains a major ingredient in the production of dried-cured pork products owing to its many technological functions [23] [24]. Sodium chloride is first of all a preservative: it protects a broad variety of food systems from microbiological spoilage and/or undesirable or pathogenic microorganisms, such as *Clostridium botulinum* and *Listeria monocytogenes*. Other sodium salts (*e.g.* sodium lactate and sodium diacetate) are also widely used in conjunction

with sodium chloride to prevent the growth of some microorganisms in many foods. Hence any reduction in the amount of salt added to a food product may generate a real microbiological hazard, potentially shortening product shelf-life and endangering human health. Taormina [25] reviewed the antimicrobial properties of sodium chloride in foods, and addressed the impact of reducing and replacing salt and sodium on microbiological food safety and quality. Secondly, salt helps to give dried-cured pork products their characteristic flavor. Thirdly, it plays a preponderant role in the final texture of the products, for example, by its action on solubilizing the meat myofibrillar proteins. In dry-cured ham, the salt controls the enzymatic activity inside muscles by inhibiting certain proteases, such as cathepsins and aminopeptidases, thus governing the time course of proteolysis [26]. The production of dried-cured pork products with low sodium chloride content is thus far from straightforward, given the major role played by salt, as such products will not only be less salty, but will also lose some of the typical flavor of dried-cured meat [27]. The likely adverse effects of reducing sodium chloride content in dried-cured pork products include poor texture due to intense proteolysis, and poor cohesiveness, which becomes a problem when the meats are sliced, together with a reduction in the flavor and aroma typical of these products [28].

Several strategies can be used to reduce the sodium content of dried-cured pork products: direct reduction of salt level over time, partial substitution of salt by other metal salts, and the use of flavor enhancers [29].

2.1. Direct Reduction of Sodium Chloride in Dry Pork Products

The simplest way is to reduce, directly and gradually—or “by stealth” as described in [29]—the quantity of sodium added when the products are being manufactured [6]. This has been done by many producers over the last decades. In 1982, it was claimed that a maximum reduction of 25% in sodium content could be achieved in most processed meat products with no detrimental effects on their flavor, texture or shelf-life [30]. However, there are few studies in the literature in which the quantity of added sodium chloride has been simply reduced. We may cite Benedini *et al.* [28], who found that in Parma hams a simple reduction of 5.5% to 4% in salt content (total mass) resulted in notable changes in texture, aroma and taste. Even so, they report that the production of Parma hams with conserved organoleptic properties and a salt content reduced by 25% is possible, provided the ripening time is extended and the proteolysis is controlled. In another study on Corsican hams aged 18 months a reduced salting time resulted in a decrease in salt content, of 7.3% - 4.7%, but also caused rancid and buttery odors linked to the oxidation of lipids, which damaged the final acceptability of this type of product by the consumer [31]. Andrés *et al.* [32] and Costa-Corredor *et al.* [5] found a loss of salt taste and aroma, and a softer texture, detrimental to overall quality in Iberian hams and restructured Spanish hams that had undergone a 50% reduction in salt content during manufacture. The same degree of salt reduction applied to smoked dried Portuguese sausages

resulted systematically in significantly higher values of a_w and pH ($p < 0.05$), variations in proteolysis, and ultimately in different aromatic profiles [33]. These studies show tendentially that it is very difficult to reduce sodium content by more than 25%, by simply lowering the quantity of sodium chloride added to the pork products during their manufacture, without adversely affecting texture and/or aroma. In addition, for dried-fermented products, sodium chloride content cannot be simply reduced, because a low a_w value still has to be reached to ensure the microbiological stability of the products [27].

2.2. Partial Substitution of Sodium Chloride by Other Salts in Dry Pork Products

Another very widely applied strategy consists in replacing some of the sodium chloride (NaCl) by substitute salts, in particular by potassium chloride (KCl), calcium chloride (CaCl_2), magnesium chloride (MgCl_2), potassium lactate ($\text{C}_3\text{H}_5\text{KO}_3$) or calcium ascorbate ($\text{C}_{12}\text{H}_{14}\text{CaO}_{12}$), which allows the overall sodium content to be lowered, while controlling a_w inside the products. The substitute salt most often used is potassium chloride, because of its similar behavior in terms of protein solubilization and inhibition of protease activity [34]. However, at high concentrations, potassium chloride generates a strong bitter, metallic taste in products. For example, Gou *et al.* [35] highlighted unwanted bitterness in dry-fermented sausages, when a degree of substitution of sodium chloride by potassium chloride reached 30%. However, other authors found that this defect remained acceptable up to a substitution rate of 40% - 50%, in particular in small-diameter fermented sausages [36]. Gou *et al.* [35] also found aroma and taste defects at rates of substitution by potassium lactate and glycine equal to 40%, together with problems of texture (*i.e.* lower cohesiveness) for rates of substitution by potassium lactate and glycine of 30% and 40%, respectively. Gelabert *et al.* [37] obtained much the same results, with the appearance of flavor and texture defects, from a rate of sodium chloride substitution by KCl of 40%, by potassium lactate of 30%, and by glycine of 20%. These authors also found that replacing 40% - 70% of NaCl by mixtures of KCl and potassium lactate, and of potassium lactate and glycine, was counterproductive given the severity of the flavor and texture defects observed. Gimeno *et al.* [38] [39] also found lower scores for texture and color intensity, and therefore a lower sensorial acceptability, when using mixtures of potassium, magnesium and calcium chlorides as partial replacers of NaCl during dry-fermented sausage manufacture. By contrast, Ibañez *et al.* [40] [41] found no significant differences between control sausages manufactured with 3% NaCl and others manufactured with 1.5% NaCl and 1% KCl. For more voluminous products like dry-cured hams, Aliño *et al.* [42] found that the partial substitution of sodium chloride by other salts had the effect of slowing the fall in a_w inside the product; this then required extending the low-temperature post-salting rest phase by 32%, after salting with 50% NaCl + 50% KCl, and by 52%, after salting with 55% NaCl + 25% KCl + 15% CaCl_2 + 5% MgCl_2 , to obtain values of a_w similar to those of control hams (100% NaCl),

and ensure the microbiological stability of these products in the rest of the manufacturing process. The authors account for the difference by the fact that divalent cations (Ca^{2+} , Mg^{2+}) remain mostly at the surface of the ham, where they interact with proteins, slowing their diffusion toward the interior of the muscle. These results and observations are in line with those obtained previously by Blesa *et al.* [43]. Using the same salt mixtures as [42], Armenteros *et al.* [44] highlighted defects in the sensory attributes of hams containing CaCl_2 and MgCl_2 , while hams manufactured with 50% KCl scored better, except for their taste, which presented an excessive bitterness probably due to the added KCl. These authors showed that the defects due to a 50% NaCl reduction in restructured dry-cured hams could be counterbalanced by adding K lactate, and by performing the ham drying step at 15°C , up to a final product weight loss of 45% [44]. For the same type of hams, Fulladosa *et al.* [45] observed no negative impact of adding K lactate on the main ham sensory attributes, *i.e.* color, flavor and texture.

2.3. Enhancement of the Salty Taste Perception of Low-Salt Dry Pork Products

The main defects generated by using substitute salts can be corrected by adding taste enhancers or masking agents, many types of which are commercially available [16]. For example, dry-fermented sausages were manufactured in which 50% of the sodium chloride was replaced by potassium chloride, and to which were optionally added lysine, and taste enhancers disodium guanylate and disodium inosinate, at 600 mg/kg [46]. The substitution of NaCl by KCl did not significantly modify either fermentation or the drying process, but defects of aroma, taste and texture, impairing overall product quality, were detected by a panel of consumers. All these defects were subsequently corrected by combined addition of lysine and the two taste enhancers. This study shows that it is possible to manufacture dry-fermented sausages that are sensorially quite acceptable provided taste enhancers are added, and in which the sodium content is reduced by 50% [46]. It must be underlined that in none of the studies presented so far did any health or safety problem arise due to the growth of harmful microorganisms.

Several very recent studies have also shown the high potential of adding yeast extracts to enhance the aroma of low-salt, low-fat dry-fermented sausages. Campagnol *et al.* [47] demonstrated that supplementation with a 2% concentration of yeast extract in 50%-sodium-reduced dry-fermented sausages increased the production of volatile compounds, thus helping to suppress the sensory defects caused by the KCl addition, and yielding dry-fermented sausages that presented very acceptable sensory qualities. More recently, Corral *et al.* [48] [49] and Flores *et al.* [50] confirmed that the appropriate selection and use of yeast extracts presenting aroma potential, such as *Debaromyces hansenii*, could offer a good strategy to enhance the sensory characteristics of reformulated dry-fermented sausages, in particular their aroma and taste qualities, but not their texture.

However, the beneficial effect due to the yeast inoculation is far from clear when both sodium and fat reductions are combined during the dry sausage manufacture [49]. Yeast strains can also be inoculated and used as masking agents to improve the physical, chemical and sensory properties of dry-fermented sausages manufactured with entire male fat. Very recently, Corral *et al.* [51] showed that the inoculation of a *Debaromyces hansenii* strain regulated water release during ripening owing to the surface yeast growth, and lowered hardness and chewiness in dry sausages containing entire male back fat, thus conferring textural properties similar to the control products containing gilt back fat.

One further way to modulate salty taste perception is to modify the physical structure (*i.e.* crystal size and shape) of the sodium chloride [16] [23]. Reducing the size of undissolved salt crystals may produce a much faster dissolution in the consumer's mouth, and so a prompter and more intense perception of the salty taste of the product, even if the total quantity of salt is lower [52]. In their review, Weiss *et al.* [23] indicate that a change in the physical state of the salt from crystalline to amorphous allows a 20- to 100-fold reduction in sodium chloride particle size. However, the perception of a salty taste and the salt-brain relation underlying it require further research to elucidate the mechanisms in play and find ways to "mislead" the brain [53]. For example, Lawrence *et al.* [54] have shown that certain carefully chosen odors (bacon and anchovy, among others) can compensate for defects arising from a reduction of sodium chloride content in solid foodstuffs. This strategy, called odor-induced saltiness enhancement (OISE), was also successfully tested for enhancing saltiness in low-salt content cheese models [55]. Recently, the approach using congruent aromas was even extended to compensate for loss of both saltiness and of fat perception in low-fat and low-salt cheese-like solid foods, thus highlighting a complex interaction between the effect of the composition and structure of the products and the odor-induced salt and fat perception enhancement [56].

3. Reduction/Substitution of Animal Fat in Dry-Fermented Sausage

As a result of drying, pork products like dry-fermented sausage or salami can ultimately contain 30% - 50% animal fat. This fat proportion is a major determinant of the final sensory characteristics (flavor, texture, juiciness and appearance) of this type of product. It also manifestly deters persons with cardiovascular diseases or who are overweight from consuming these products [23]. Besides the quantity of fat consumed, its qualitative composition impacts strongly on human health. For example, ensuring cardiovascular health demands a very low consumption of *trans* fatty acids (less than 1%) and a sufficient supply of polyunsaturated fatty acids (PUFAs 6% - 10%) in the daily energy intake, with the further constraint that these PUFAs should be well balanced between ω -6 (5% - 8%) and ω -3 (1% - 2%), with a ratio of 1 - 4 [17]. However, today's Western diets are poor in ω -3 and very rich in ω -6 PUFAs, with a ω -6/ ω -3 ratio between 15 and 20, very far from what is advocated [57]. Reducing the animal fat content of

dry-fermented sausages may require reformulation of the product. A product composed of lean meat, vegetable instead of animal fat, and other fat substitutes, associated with appropriate manufacturing conditions, can help modify the lipid profile and fat concentration [23].

3.1. Direct Reduction of Animal Fat in Dry-Fermented Sausage

Simply reducing the animal fat content leads predictably to a loss of aroma, often not readily accepted by the consumer. From experiments on dried sausages in which fat content ranged between 10% and 30%, Olivares *et al.* [58] found that the reduction in fat slowed lipolysis, lipid oxidation, and the ensuing formation of volatile compounds. Their results also showed that consumer acceptance was closely correlated with high fat levels and long ripening times. In a preceding study, Olivares *et al.* [59] had determined that the limit between acceptability and rejection by consumers of fat-reduced dry-fermented sausages corresponded to an initial fat content of 16%, which leaves room for a reduction of about 50% relative to the trade standard. Lorenzo and Franco [60] have shown that high fat levels confer a bright color and a more flexible texture, and favor the production of free fatty acids, in the case of sausages manufactured from a mixture of horse meat and pork fat (5% - 20%). In addition, several very recent studies report on work designed to substitute some of the animal fat by cellulose gels derived from maize fiber, or konjac glucomannane, a polysaccharide extracted from a plant native to South-East Asia. Campagnol *et al.* [61] have shown that it is possible to replace 50% of pork fat by a cellulose gel without adversely affecting the quality of the sausages, and manufacture products with fat and cholesterol levels reduced by 45% and 15%, respectively. Despite some differences in texture, dry-fermented sausages, in which 50% and 80% of pork fat were replaced by konjac gel, were judged acceptable by a panel of tasters [62]. Very recently, Alejandre *et al.* [63] successfully investigated a high ω -3 content carrageenan gelled emulsion as an animal fat replacer in order to improve the fatty acid composition of dry-fermented sausages. They showed that the level of animal fat replacement could reach 32.8% without causing any relevant defects in terms of instrumental color properties, taste and juiciness of end products.

3.2. Incorporation of Dietary Fiber in Dry-Fermented Sausage

The consumption of dietary fiber is known to be beneficial to human health. Accordingly, many recent studies have set out to quantify the effect of adding fiber, often of plant origin, as a functional ingredient, on the sensory and health safety properties of dry-fermented sausages with reduced animal fat content. García *et al.* [64] studied the effect of adding fiber from fruits (peach, apple and orange) and cereals (wheat and oats), at concentrations of 1.5% and 3%, on the sensory properties of dry-fermented sausages initially containing only 6% and 10% pork fat. The best sensory results were obtained for sausages manufactured with 10% pork fat and 1.5% fiber from oranges. Adding more fiber yields products that are too hard, and that present problems of cohesiveness. These results

confirm those of Fernández-López *et al.* [65], who showed that it was possible to add 1% orange fiber during the manufacture of sausages without harming flavor. This addition also seems to protect against the formation of rancidity, and leads to a decrease in residual nitrite level. The same type of result was obtained in dry-cured sausages, when incorporating up to 50 g·kg⁻¹ dehydrated raw lemon albedo or 75 g·kg⁻¹ dehydrated cooked lemon albedo [66]. Mendoza *et al.* [67] also tested the incorporation of powdered inulin, and demonstrated the feasibility of manufacturing dry-fermented sausages with 40% - 50% less pork fat, and 30% fewer calories, but enriched with 10% dietary fiber. Adding fiber from carrots is another possibility, provided its concentration does not exceed 3% to avoid products of poor quality with problems of fermentation, and subsequently of texture [68]. By developing a multi-layer feed forward artificial neural network, Eim *et al.* [69] placed at exactly 4.9% the highest content of carrot dietary fiber that could be added to dry-fermented *sobrassada*-type sausages, and that yielded end products with quality characteristics similar to the reference products not containing fiber. Recently, Sánchez-Zapata *et al.* [70] investigated the effect of adding tiger nut fiber (from 1% to 2%) alone or combined with walnut oil (2.5% - 5%) on some physical, chemical, microbial and sensory parameters in dry-cured sausages, thus demonstrating the utility of incorporating tiger nut fiber, which is rich in antioxidant compounds, to control the increase in lipid oxidation that occurs when walnut oil alone is added. Lastly, Salazar *et al.* [71] have shown that adding short-chain fructo-oligosaccharides, recognized as prebiotics, at initial concentrations of 2%, 4% and 6%, does not modify the sensory qualities of the products, while at the same time fat content could be reduced by up to 58%, and up to 8.7% of fiber introduced in the final product.

3.3. Incorporation of Oil in Dry-Fermented Sausage

Incorporating oils from plants, fish or microalgae is also a promising technological path to improving the lipid profile of sausages by increasing the levels of unsaturated versus saturated fatty acids. Among the oils tested, we may cite linseed oil at 3.3% [72], olive oil at up to 20% [73] [74], soybean oil at 20% [75], deodorized fish oil at 30% [76] [77] and oil from micro-algae at 15% [78]. Most of these oils were incorporated as emulsions, or even microencapsulated, in order to facilitate mixing with the chopped pork meat. Recently, Lorenzo *et al.* [79] manufactured Spanish *salchichón* presenting a better lipid profile by partially substituting up to 75% of the pork backfat by microencapsulated fish oil in a konjac glucomannane matrix. They concluded that this reformulation procedure was technologically feasible, but most of the sensorial properties and also lipid oxidation were significantly affected. Jiménez-Colmenero *et al.* [80] investigated the use of a healthy oil combination (olive, linseed and fish oils) previously stabilized in a konjac matrix as a pork fat replacer with the objective of enhancing the lipid composition of dry-fermented sausages. Although this reformulation procedure predictably improved the ω -6/ ω -3 ratio in the end products, at the same time it degraded all the sensorial parameters compared with controls [80].

However, as a general rule, when the oil concentrations and substitution rates exceed a certain limit, unacceptable defects ensue during dry sausage manufacture, resulting, in particular, in loss of oil. At a moderate level of incorporation, which varies according to the oil used, the dry-fermented sausages obtained present a highly significant increase in their unsaturated fatty acid fractions, and a marked reduction in cholesterol level, and so an appreciable improvement in their nutritional qualities [81]. However, care must be taken not to let adding oils increase lipid oxidation. With this in mind, antioxidants are often associated with oil incorporation. The current trend is to add naturally-occurring antioxidants extracted from plants, although they seem less efficient than synthetic antioxidants such as butylhydroxyanisol (BHA) and butylhydroxytoluene (BHT), which are suspected of favoring the formation of certain cancers. García-Iñiguez de Ciriano *et al.* [82] successfully demonstrated the ability of extracts from borage leaves at a concentration of 340 ppm per kg to retard oxidation in Pamplona chorizos enriched with ω -3 polyunsaturated fatty acids, by substitution of 25% of the quantity of pork fat by a linseed oil emulsion. In Turkish dried sausages, Bozkurt [83] showed that the efficiency of naturally-occurring antioxidants like sesame oil or the oil of *Thymbra spicata* was as high as that of BHT, as regards oxidation, and appreciably greater as regards the formation of biogenic amines such as putrescine and histamine; the three ingredients tested were all added at a concentration of 300 ppm per kg. Recently, Ba *et al.* [84] studied the antioxidant and anti-bacterial effects of extracts from shiitake by-products in dry-fermented sausages during their storage for up to 30 days, at 15°C. Analyzing their results clearly shows that this extract, when added at a level of 0.6%, strongly limited the increase in lipid oxidation during the product storage, as well as the growth of pathogens such as *Staphylococcus aureus*, *Listeria monocytogenes* and *Escherichia coli* O157 [84]. Lastly, the incorporation of carotene by adding tomato skin powder (up to 1.2%) to dry-fermented sausages was successful, and may prove an effective way to limit lipid oxidation, while at the same time making gainful use of an industrial by-product [85]. We note that the use by the food industry of antioxidants derived from industrial natural by-products, *e.g.* tomato or shiitake extracts, is to be encouraged as part of a sustainable development approach.

4. Reduction of Nitrate/Nitrite in Dried-Cured Pork Products

The use of nitrate in pork products goes back to ancient times. The first explanations for its mode of action were given at the end of the 19th century. In 1901, Haldane (cited by Dabin and Jussiaux [86]) was the first to account for the effect of nitrite on meat color, which occurs after the binding of nitric oxide (NO) by myoglobin. The valence of iron (Fe^{2+} or Fe^{3+}) contained in myoglobin determines its color. Oxidation of the iron and simultaneous binding of nitric oxide from the reduction of nitrite causes nitrosometmyoglobin to form, which in turn is reduced to nitrosomyoglobin, the red color of which is stable at low a_w values. Unlike nitrate, nitrite also has a bacteriostatic or even bactericidal action, in par-

ticular on *Clostridium* and enterobacteria such as *Salmonella* and coliforms. Lastly, both nitrate and nitrite give meats the taste and odor characteristic of salted-dried products. Nitrite limits lipid oxidation and retards the development of rancidity, and so forestalls the appearance of undesirable flavors during storage [23]. In the manufacture of dried-cured pork products with long ripening times, nitrite is the active substance in salting-drying, nitrate acting as a reserve for nitrite formed by microbial action throughout the process [87].

Nitrite is toxic when consumed in large doses. It converts hemoglobin into methemoglobin, which prevents all oxygen transport to the tissues in the body, causing cyanosis if more than 20% of the hemoglobin is converted. Nitrite is some 10 times more toxic than nitrate: in humans, the lethal oral doses are in the range 80 - 800 mg of nitrate/kg body weight and 33 - 250 mg of nitrite/kg body weight [88]. In addition to this direct toxicity, nitrite can also indirectly combine with amines derived from the breakdown of meat proteins, for example during proteolysis. Under certain conditions (temperature above 130°C, acidic medium), nitrosamines are formed, some of which are recognized mutagenic substances that can induce carcinogenic effects [89] [90]. The use of nitrate/nitrite is thus regulated in many countries, where nitrite may be used only as a mixture with sodium chloride containing less than 1% nitrite ("curing salt"). Since 2006 in France no more than 300 mg/kg of nitrite plus nitrate can be added to unheated pork products to be dried and ripened. However, it is generally accepted that in the human diet, most nitrite comes from dried-cured meat products, but most nitrate (70% - 90%) is supplied in vegetables and drinking water. Hsu *et al.* [91] recorded nitrate concentrations of up to 5000 mg/kg in spinach; in meat products, the highest value was found in salamis, with 140 mg/kg. For nitrite, these same authors found levels below 87 mg/kg and 23 mg/kg in meat products and vegetables, respectively. Alongside exogenous intake due to direct ingestion of nitrite, nitrate is converted into nitrite in the human mouth and stomach [92], forming an endogenous nitrite source that may be responsible for most of the nitrite present in the stomach. Because of its acidity, and the presence of large amounts of nitrite, the stomach makes a very good reactor for the synthesis of nitrosamines. Exposure to endogenously-formed nitrosamines has been associated with increased risk of cancers of the stomach, esophagus and bladder [93]. Moreover, Joosens *et al.* [94] highlighted a synergistic effect of dietary nitrate and high sodium intakes as risk factors for stomach cancer mortality. Accordingly, although residual levels of nitrate and nitrite present in dried-cured pork products are not hazardous, except in the case of a manufacturing accident, there is strong pressure of public opinion to minimize or even ban the use of nitrate in foods, including dried-cured products.

Like for sodium chloride, the reduction or even the complete banning of nitrate/nitrite is far from straightforward, because of the many reactions both positive and negative caused by contact between nitrite and the different components of the meat matrix, and can raise problems. This complexity prompted Jiménez-Colmenero *et al.* [95] to assert that it would be impossible to find a sin-

gle substance able to perform all the functions of nitrite. Only combinations of several substances could be expected to produce the positive effects of nitrite on color and aroma, and exert its antimicrobial and antioxidant activities. Pichner *et al.* [96] confirmed that simply removing nitrate and nitrite from salamis, without sufficient technological knowledge to correct the process, led to products of very poor quality, both sensory (no typical coloration at the core of the products) and microbiological (survival of Gram-negative bacteria). In their study, Hospital *et al.* [97] also confirmed the essential barrier role played by nitrate/nitrite, in the same way as pH and a_w , against the growth of *Salmonella typhimurium* in dry-fermented sausages. Not adding nitrate/nitrite to the meat batches led to an increase of 2 - 2.5 log cfu/g in the *Salmonella* population in the end products. However, these authors observed experimentally that reducing the amount of nitrate and nitrite by 50% led to the same inhibitory effect against *Salmonella typhimurium* as the maximum amount allowed by the EU (300 mg) [97].

One other way to reduce direct addition of nitrite and nitrate is to incorporate nitrate-rich powdered vegetables (celery, beetroot, and leek, among others). This requires adding microbial flora to ensure the reduction of nitrate to nitrite. Tsoukalas *et al.* [98] have shown that adding 0.84% leek powder, supplying 75 mg/kg of nitrate, associated with 75 ppm of nitrite, in no way modified the fermentation and drying steps, and allowed the same organoleptic and sensory qualities to be conserved during the manufacture of dry-fermented sausages. This addition allowed a 50% reduction in the use of nitrate, and eliminated the use of “chemical” nitrate. From a trial conducted with a stepwise assay of nitrate, Schlüchter *et al.* [99] showed that during the manufacture of salamis, saltpeter, a source of nitrate, could be partly replaced by powdered vegetables, with no microbiological hazard. However, high levels of vegetable powder gave the salami lower peelability and a firmer consistency. In addition to directly reducing the quantity of nitrate and/or nitrite added during manufacture, one possible approach would be to intervene directly in the chain of reactions leading to the formation of nitrosamines, using antioxidants such as vitamin C, polyphenols, ascorbate, or erythorbate, which would inhibit their formation [95] [100].

The issue of nitrate/nitrite in dried pork products is compounded by the seemingly paradoxical case of Parma ham, to which sodium chloride alone is added during manufacturing, without any microbiological problem or color defect occurring. Even though no nitrate or nitrite is added to the sodium chloride, the color of Parma ham is “mysteriously” bright red, and highly stable. Wakamatsu *et al.* [101] suggested that the typical red color of Parma ham came from a substance, zinc protoporphyrin IX (ZPP), in which the iron atom of heme has been replaced by an atom of zinc, a metal abundant in pork. The enzyme zinc-chelatase was thought to be involved in this reaction, by catalyzing the substitution of iron by zinc; the activation of this enzyme may be greater in the presence of salt [102]. A few years later, Wakamatsu *et al.* [103] found there was in fact no iron-zinc substitution in heme, but instead the insertion of an atom of zinc di-

rectly in protoporphyrin. More recently, Wakamatsu *et al.* [104] went on to show that adding nitrite to dried-cured pork products, through the formation of nitric oxide (NO), inhibited the formation of protoporphyrin IX, the precursor of the protoporphyrin-zinc IX complex, responsible for the typical color of Parma ham. This mechanism may explain why the ZPP complex occurs in small quantities in dried-cured pork products in which nitrite is incorporated, in contrast to Parma ham [105]. In addition to sodium chloride, it would seem that adding ascorbate enhances the formation of ZPP. This mechanism thus offers an interesting avenue for obtaining satisfactorily colored dried-cured pork products without adding nitrite.

The use of nitrate/nitrite in the manufacture of dried-cured pork products draws criticism and remains controversial. Should these substances be banned, given the direct and indirect toxicity of nitrite? Or should they continue to be authorized in strictly limited quantities, in view of their many positive effects on the sensory and health safety qualities of dried-cured pork products? These questions remain open, especially since several recently published studies have pointed to the positive human health benefits of a diet rich in nitrate/nitrite, through the formation of nitric oxide, deficiency of which has been demonstrated medically to cause several health disorders [106] [107] [108] [109]. Lundberg *et al.* [107] go further, advocating a fresh view of nitrate/nitrite, looking at it not as a threat to human health, but rather as an essential nutrient in our diet. Parthasarathy and Bryan [109] conclude by reminding us of the dual meaning of the term “cure”, suggesting that the ancient “curing” agent nitrate/nitrite might soon be seen more as a health “cure”. What is certain is that further studies are warranted to elucidate all the mechanisms involved in the nitrite chemistry and its interactions with the components of the meat matrix, both during the manufacture of the cured red meat products and during the digestion in the human stomach and gut of these meat products, which are commonly consumed, in a diet, in combination with water, fruits and vegetables.

5. Toward Dried-Cured Pork Products with Higher Nutritional Value

Reducing the sodium content of dry-cured pork products, and associating a reduction in their animal fat content, manifestly helps improve the nutritional value of these food products. Although the scope for action seems more limited than for cooked pork products like frankfurters, several studies have been conducted in recent years to further improve the nutritional profile of dry-fermented pork products (sausage, salami, *etc.*), by modifying their lipid profile or by incorporating dietary fiber or naturally-occurring antioxidants. Dry-fermented sausages to which probiotics have been added have even been successfully produced [110] [111]. Several recent reviews deal with this subject [23] [81] [95] [100] [112] [113] [114] [115] [116]. However, whenever a new substance is incorporated, or sodium or fat contents are changed, it is essential to evaluate the consequences of these changes on the organoleptic, health safety and sensory

qualities of the “new” products. Furthermore, all the qualities of these new products are most often expected to resemble those of the equivalent unmodified product, whereas some differences are inevitable, in particular in the typical flavor. This may therefore not be the best approach to successfully market pork products with improved nutritional qualities.

Until the last two years, there have been very few studies on combining sodium and animal fat reductions in dried fermented pork products, doubtlessly because these two reductions jointly cause a very marked loss of the aroma and typical taste expected of such products. These studies include the work of Beriain *et al.* [117] designed to quantify the effect of replacing half the pork fat by an emulsion of water, olive oil and alginate, incorporating inulin, and substituting 58% of the sodium chloride by 20% potassium chloride and 38% calcium chloride, on the qualities of Pamplona chorizo. Trials showed that the incorporation of olive oil in an emulsion, associated with a 58% reduction of sodium chloride, had no negative effect on the technology of the manufacturing process, no abnormal difference in the time course of pH or microbiological populations being detected at any time during manufacture. Chorizos containing alginate were shinier and harder than traditional ones, except for those also containing 6% inulin. In conclusion, this work showed that by combining the incorporation of an emulsion based on alginate and olive oil with added inulin, it was possible to manufacture Pamplona chorizos with less salt and less fat, but with more unsaturated fatty acids, thereby offering products with a better nutritional profile than those manufactured traditionally [117]. Recently, Safa *et al.* [118] investigated the effect of direct combined salt and animal fat reductions on the time course of several physical, chemical and biochemical parameters during the manufacture of dry-fermented sausages. Briefly, their results showed that direct combined salt and fat reductions increased the acidification, product weight losses and final a_w , amplified the proteolysis and lowered the lipolysis and protein and lipid oxidations, thus probably altering the end product sensory attributes. In another very recent study [119], the same authors quantified the effects of combined partial substitutions of NaCl by KCl and of pork backfat by sunflower oil on key physical, chemical and biochemical parameters, on end product instrumental color and texture, and finally on the consumer acceptability of the new dry-fermented sausages manufactured. They demonstrated that sodium and SFA contents can be drastically reduced in dry-fermented sausages (up to 30% for sodium and 60% for SFA, respectively) without too marked defects in final textural properties, color or consumer acceptability [119]. The same type of study was performed for small-caliber non-acid fermented sausages by Mora-Gallego *et al.* [120], who found that a combined reduction of NaCl and fat contents, from 2.5% to 1.5% and from 33.2% to 15.1%, respectively, increased consumer acceptability, and also a_w . This increase in a_w was then partially offset by adding 0.64% KCl and 1.5% sunflower oil, which finally constituted the formulation preferred by consumers.

Dry-cured ham, which takes from 6 to sometimes more than 24 months to

manufacture, is a whole product treated by surface salting. Hence the only scope for action is a reduction in the sodium content, offset by an increase in potassium or calcium content. However, care must be taken when modifying the process, given that some studies [42] [43] have shown that simply replacing about 50% of the sodium chloride by other salts increased the post-salting rest phase by 30% - 50%, depending on the salts used, owing to the increase in the value of a_w . When studying the reduction of sodium content in dry-cured hams, X-ray tomography is a useful tool for the continuous non-destructive monitoring of salt and water transfers throughout the manufacturing process. Recently, Fulladosa *et al.* [121] and Santos-Garcés *et al.* [122] [123] showed that water and salt contents, together with a_w , could be estimated at different stages in the manufacture of dry-cured hams, from images obtained by X-ray tomography. Ultimately, by favoring the formation of the zinc-protoporphyrin complex responsible for the stable red color typical of Parma ham, the incorporation of nitrate/nitrite could also be discontinued in other types of dry-cured ham.

Incorporating salts containing potassium as a sodium chloride substitute in dried-cured pork products may offer one way to increase potassium consumption in the human diet, which is generally very deficient in the populations of developed countries. Very recently, Aburto *et al.* [124] obtained statistical results suggesting that increased potassium intake is potentially beneficial to persons with no kidney disorder for the prevention and control of elevated blood pressure and stroke. We note that according to Castro and Raji [125], human well-being in terms of blood pressure and cardiovascular health may be related to the sodium-to-potassium diet intake ratio rather than to each nutrient rate taken individually. These authors thus advocate implementing a low sodium-high potassium diet as a crucial strategy for both preventing and treating human hypertension and cardiovascular disease. Moreover, it would seem that potassium intake at recommended level constitutes an optimal strategy to protect the skeleton against osteoporosis, because it prevents sodium chloride-induced calciuria [7].

Processed meat products may also become a very useful way to supply calcium in the human diet, as they are consumed by all population age groups. Accordingly, Gimeno *et al.* [126] tried adding calcium ascorbate (26% - 50% of recommended daily intake) to dry-fermented sausages, with the aim of reducing the sodium chloride content of these products (from 15% to 45%). In summary, their work showed that the use of calcium ascorbate was an efficient way to reduce sodium content in dry-fermented sausages, while at the same time enriching them in calcium ascorbate. However, no sensory testing was done on these products. Adding calcium to meat products thus seems to be a nutritionally important avenue, especially as several recent studies in rats show tendentially that intake of calcium (here as calcium carbonate) at the same time as red meat is beneficial in reducing colonic cancer risk [127] [128]. However, as calcium traps heme iron, problems may arise, given that iron deficiency is one of the most common nutritional disorders in certain population groups, in particular preg-

nant women. To avoid excessive trapping of heme iron, while at the same time reducing the risks of carcinogenesis linked to the consumption of red meat and dried-cured pork products, another approach would be to limit lipid peroxidation and the formation of nitrosamines by incorporating antioxidants in foods [127].

Besides sodium, SFAs and nitrite, dry-cured pork products are also criticized for their high cholesterol levels. Nutritional recommendations prescribe a daily intake of cholesterol in food no higher than 300 mg. Meat generally contains 77 - 95 mg of cholesterol per 100 g, except for some offal, which contains more than 300 mg [129]. We emphasize that replacing some of the animal fat by lean meat does not necessarily mean that cholesterol levels are lowered, as the cholesterol and fat contents of meat are not correlated [95]. An effective way to reduce cholesterol level in dried-cured pork products is to replace some of the lean meat and the animal fat by proteins or fat of plant origin, as plant tissues contain little cholesterol. Another way to address the issue of cholesterol in dried-cured pork consumption would be to increase their conjugated linoleic acid content [23].

6. Conclusion

Reducing the levels of sodium and saturated fatty acids in dried-cured pork products, and no longer adding nitrate/nitrite, thereby enhancing the nutritional value of these products, are central to current issues facing meat professionals, *i.e.* manufacturers, technologists, researchers, applied scientists, etc. These actions seem essential to restore the public image of processed pork products, especially now that many consumers are ready to accept dried-cured products that are salt-reduced, fat-reduced and nitrite-free [130]. The consumption of dried-cured pork products is nutritionally beneficial in terms of ingested proteins, because of their concentration after drying, and given their essential amino acid profile, which is well-balanced and close to human requirements. Knowing what we eat, and keeping to a varied, balanced and moderate diet, are essential factors in healthy human nutrition. Achieving a balanced diet is the consumer's responsibility, but the food industry, and in particular the meat industry, must be able to provide the consumers with a broad range of products that meet their demands. This will only be possible if a multidisciplinary approach is set up associating scientists (food scientists, process engineers, modeling experts, microbiologists, biochemists, toxicologists, nutritionists, etc.), pork professionals and technologists, leading, for example, to the development of computer-aided decision-making tools, making it possible to virtually design either the dry-cured meat products or the manufacturing processes associated with these foodstuffs. The "numerical dry-cured ham" model recently built [131] offers a good example of the type of numerical tools we will have to develop in the near future to help professionals manufacture new, healthier dry-cured meat products.

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