Agricultural Science and Food Processing
http://dx.doi.org/10.62762/ASFP.2024.261094

REVIEW ARTICLE

Salt Reduction in Processed Meats: Current Advances and Future Directions

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Abstract

The paper discusses the multiple functions of salt in meat products, such as enhancing flavor, adjusting texture, reducing water activity, inhibiting bacteria, and extending shelf life. It also emphasizes the global health concern of excessive sodium intake and the necessity of reducing salt in processed meats to address this issue. Additionally, this paper presents the importance of reducing microorganisms in meat products through the use of sodium chloride and additives like sodium nitrite to ensure product safety. Furthermore, it highlights the strategy of changing the physical structure of salt to reduce salt content without compromising product quality, such as using 3D printing technology to control salt distribution on the food surface and micronization technology to enhance saltiness while reducing salt usage.

Keywords: meat product processing, salt reduction, sodium chloride, non-sodium salt substitution.

Academic Editor:
Jie Ouyang

Submitted: 21 September 2024
Accepted: 22 October 2024
Published: 05 November 2024

Vol. 1, **No.** 1, 2024.
10.62762/ASFP.2024.261094

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1 Introduction

Salt, primarily composed of sodium chloride (NaCl) with a few additives, is a ubiquitous condiment in meat processing. Beyond imparting a salty taste, salt serves multiple functions in meat products, including enhancing flavor, adjusting texture, reducing water activity, inhibiting bacteria, and extending shelf life [1]. It promotes protein dissolution and gel formation, improving water-holding capacity, reducing cooking losses, and increasing product yield. However, excessive NaCl can accelerate lipid oxidation, impacting flavor and color [2]. Sodium chloride is crucial for maintaining the internal environment of human body fluids, regulating osmotic balance, and supporting various physiological functions such as muscle contraction, heart function, and nerve impulse transmission. Processed foods contribute significantly to total salt intake, with meat products being substantial contributors in many regions globally. However, excessive intake of sodium ions has become a global health issue [3]. Data shows that 99.4% of the world's population consumes more sodium than the recommended daily intake [4]. It is also positively associated with the incidence of cardiovascular and cerebrovascular diseases, primary liver cancer, and atrial fibrillation (Figure 1).

In meat, there is naturally a small amount of salt present. However, to produce better quality meat

Citation
Zou, T. (2024). Salt Reduction in Processed Meats: Current Advances and Future Directions. *Agricultural Science and Food Processing*, 1(1), 4–20.

products, a certain amount of table salt is often added during processing, resulting in a significant increase in the salt content of the products, as shown in Table 1. Therefore, reducing the use of inorganic or organic sodium salts is also necessary for low-salt meat products, and soy sauce and other condiments and meat products have become the main objects of salt reduction.

1.1 Texture Enhancement

Salt significantly influences the quality and texture characteristics of meat products. Higher salt levels within a specific range lead to better yield and Water-Holding Capacity [6]. Salt promotes protein hydration and enhances protein-protein and protein-fat binding, stabilizing the emulsification of meat products with fat. Products with low salt levels may exhibit texture defects due to unstable emulsification, while excessive reduction in salt content can result in softer texture and undesirable flavors [7].

Table 1. Sodium and salt content in processed and unprocessed meat.

Process	Product/100g	Na/mg	Salt/g
Raw	Beef	63	0.16
	Pork	70	0.18
	Chicken meat	60	0.15
	Turkey	50	0.13
Processed	Beef burger	290–400	0.71
	Sausage	600–1,080	1.5–2.7
	Frankfurter sausage	720–920	1.8–2.3
	Cooked ham	900–1,220	2.3–3.0
	Bacon	1,000–1,540	2.5–3.9
	Chicken with bread	200–420	0.5–1.1
	Nuggets of chicken	600	1.5

Note: Source is the USDA National Food Database.

1.2 Flavor Enrichment

Salt enhances flavor by modifying the perception of saltiness, particularly in products with higher fat content [8]. It influences the oxidation of proteins and lipids, thus affecting the flavor profile of meat processing [9]. Salt promotes lipid oxidation, which contributes to the volatile flavor compounds of meat products. Additionally, it promotes protein hydrolysis, generating free amino acids and peptides, which are key components of flavor. Reducing salt content can impact the flavor characteristics of meat products, depending on the type of meat product and the extent of salt reduction [10].

2 Current Advance of Low-salt meat Products Processing Technology

The taste of salt is recognized by taste buds located on the mucous membranes on both sides of the tongue. These taste buds consist of taste receptor cells (TRCs), which serve as sensors for specific taste-related compounds. Sodium ions selectively pass through epithelial sodium channels (ENaC) located at the apex of receptor cells, causing depolarization and signal transduction, thereby activating synapses and stimulating incoming nerve fibers. The signal is then transmitted to the taste cortex of the brain, where it is encoded into a "taste map" composed of different hotspots, ultimately leading to adaptive taste perception [11].

The most direct method to reduce salt content in food is to gradually decrease the amount of NaCl added during processing. Quadros et al. [12] found that reducing the salt content of Spanish mackerel burgers from 1.5% to 0.75% resulted in a 50% reduction in sodium content, with no significant changes in product quality parameters, indicating the feasibility of directly reducing salt addition. However, reducing salt content in meat products not only diminishes saltiness but also raises other issues. Firstly, reducing salt addition can shorten the shelf life of products. Cerón-Guevara et al. [13] found that decreasing salt levels in frankfurter sausages accelerated the growth rate of natural bacterial flora. Secondly, there is an impact on sensory quality. In the production of frankfurter sausages, severe issues in appearance and palatability arise when the total salt content decreases to 1% to 1.5%. Reduction in salt may affect moisture and fat binding in the product, thereby compromising texture. Therefore, direct reduction in salt addition needs to be gradually implemented to allow consumers to adapt to low-salt products, which will take a considerable amount of time to achieve the desired outcome. Other techniques are also needed to compensate for the negative effects of reduced NaCl addition.

Current low-salt meat processing techniques primarily include several aspects: Firstly, partial substitution of sodium chloride in table salt with non-sodium salts, such as using salty-tasting salts like chloride, lactate, and phosphate singly or in combination to achieve salt reduction effects. Secondly, the utilization of savory peptides and flavor enhancers, such as using amino acid peptides with salty taste or flavor enhancers that enhance saltiness to increase

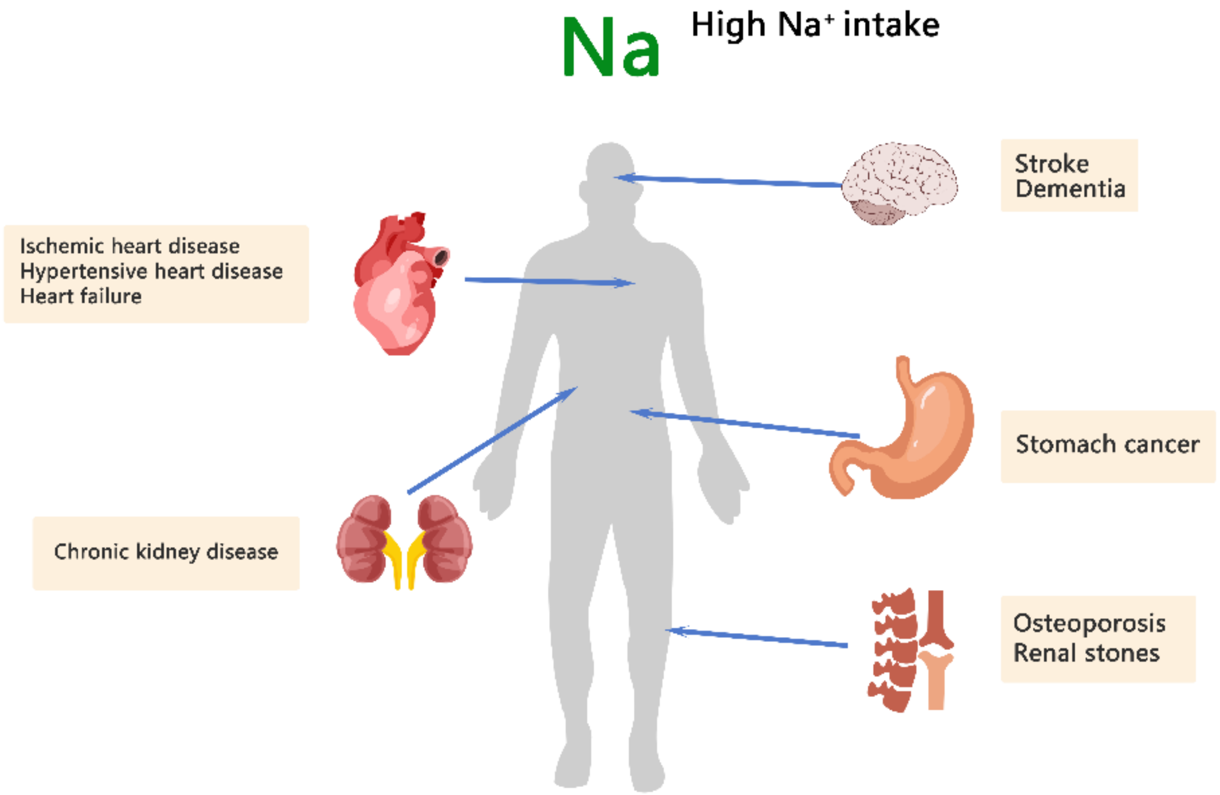

Figure 1. Health Risks Associated with excessive salt intake.

the saltiness of meat products, thereby reducing the amount of table salt. Thirdly, reducing salt content through optimized processing techniques, such as employing ultrasound, high pressure, and micronization technologies to facilitate salt penetration and decrease salt usage [14]. Fourthly, optimizing the physical structure of table salt to enhance salt perception, such as employing emerging technologies to promote sodium ion release in the oral cavity, aiming to enhance saltiness perception and reduce sodium chloride usage. Common approaches to lowering salt content include reducing the amount of sodium salt used, altering structure, substituting sodium with other salts, adding flavor enhancers, utilizing multisensory perception of saltiness , and applying various processing technologies (Figure 2). And five methods to reduce the salt content of meat snack food are shown in Table 2.

2.1 Changing the Physical Structure

Altering the configuration of salt stands out as a paramount strategy for reducing salt content without compromising product quality. The morphology and dimensions of salt play a pivotal role in its dissolution kinetics and diffusion rate. Salt particles with diminutive dimensions and expansive surface areas exhibit facile dissolution and diffusion properties. Furthermore, there exists a positive correlation between the perception of saltiness and the dissolution rate of salt. Augmenting the dissolution rate of NaCl in saliva holds the potential to amplify the transference of ions to taste receptors, thereby potentially intensifying the perceived saltiness of food items [2]. Salt on the surface of food comes into greater contact with taste buds, so 3D printing technology can be employed to control salt distribution on the food surface to reduce salt content [18]. The crystal morphology of salt also affects its dissolution rate; generally, granular salt dissolves significantly slower in the mouth compared to flake salt. Flake salt dissolves faster, making it more likely to elicit a salty taste perception in the human body. The perception of saltiness by taste buds is closely related to the way salt is delivered to them. Micronization technology can reduce large salt particles to micronized salt particles of 5 10 nm. Micronized salt dissolves significantly faster in the oral cavity and can bind more effectively with taste buds, thus maintaining saltiness while reducing salt

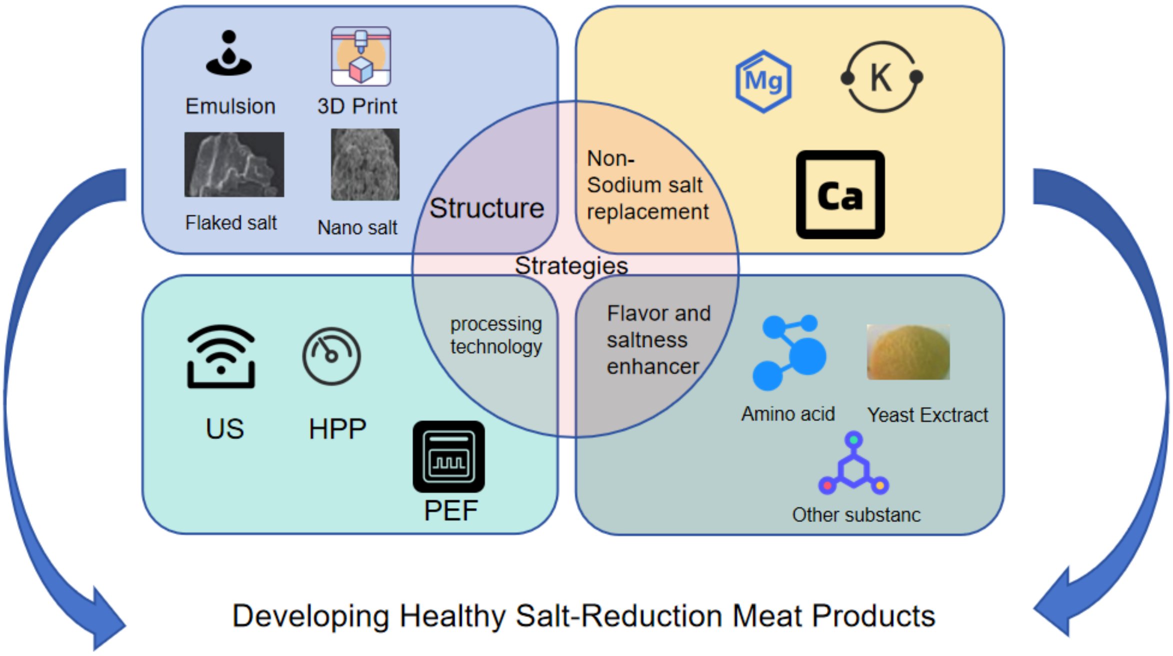

Figure 2. Salt reduction strategies in meat products.

Table 2. Methods to reduce the salt content of meat snack food.

Meat	Features	Reference
Direct salt reduction	Simple operation, but the ion intensity decreases, the emulsification and solubility of the protein worsen, and the gel structure is loose	[15]
Optimize the physical form of salt	Optimizing the physical form of salt is effective and simple, the dissolution speed of salt is fast, and the salty taste is perceived quickly	[16]
A substitute for salt was added	Effectively reduces the salt content of marinated meat, but does not affect the flavor and storage of meat products	[16]
Use new processing technology	Reducing salt content and extending product shelf life effectively improves the quality characteristics of meat products	[17]
Use of combined techniques	The combination of multiple barrier factors will significantly enhance the effect, and the good flavor of the product can be maintained	[1]

usage. Rios-Mera et al. [19] found that micronized salt, processed to reduce salt content from 1.5% to 1.0% in beef burgers, maintained the same level of saltiness. Due to the high cost of optimizing salt structure, further practical application of this technology in large-scale production of low-salt meat products requires continuous experimentation.

Smaller salt particles ensure higher salt intensity in the oral cavity compared to normal-shaped salt. As particle size decreases, sodium releases faster, exhibiting increased diffusion efficiency due to greater exposed surface area, leading to greater perceived saltiness by receptors [20]. Various techniques such as spray drying, nano-spray drying, and electrohydrodynamic atomization can be employed to produce micron and nano-scale ultrafine salt particles. Rama et al. [20] found that salt crystalline particles with a size fraction of <425 μm yield the highest salt concentration and total salt content. Granulation techniques can produce hollow-structured salt crystals, enhancing availability to taste receptors. Hollow salt provides higher sensory perception of salt by maximizing the ratio of surface area to volume. Additionally, Beck et al. [21] encapsulated salt particles with Brazilian palm wax when making sausages, creating non-uniform salt distribution to enhance salt perception. Results indicated that using encapsulated salt could maintain the taste and texture of fresh sausages while reducing salt content by 25%.

2.2 Sodium Salt Substitutes

Replacing sodium with other inorganic salts is considered to be the most common method of salt reduction. Non-sodium salt partial substitution for chloride sodium is currently the most mature technology in the research of low-sodium meat products processing. Although the physicochemical properties of potassium, calcium, and magnesium ions are similar to sodium ions, they taste metallic and bitter. The over-substitution can result in poor flavor of the product [22].

Potassium salt stands out as a prevalent substitute for traditional sodium chloride. Its presence helps to offset sodium ion levels in bodily fluids, thereby mitigating the potential risk of hypertension resulting from excessive sodium intake among consumers. The antibacterial effect of potassium ions is also the same as that of sodium ions. Replacement of 50% NaCl with KCl can still keep the WHC and textural properties of myofibrillar protein gels [2]. Vitor et al. [23] utilized potassium chloride to replace 50% of sodium chloride in beef curing, and the results indicated that the replacement had no significant effects on the physicochemical properties, microbiological indicators, and sensory characteristics of dried beef. Chen et al. found that when potassium chloride was used to replace 20% to 30% of sodium chloride in meat jerky, the low-sodium salted meat jerky exhibited higher sensory quality. In a meat soup simulation experiment, Tang et al. found that the quality of Western-style sausages was not affected when 30% of sodium chloride was replaced with potassium chloride. However, when the substitution ratio of potassium chloride exceeds 30%, it adversely affects the physical and chemical attributes, sensory qualities, and shelf life of meat products [24].

However, the excessive addition of potassium chloride adversely affected product flavor, which could be mitigated by adding amino acids for compounding to ensure a good taste of the food. The material ratio of compound salt and the production process also have a certain impact on the final product flavor. Dong optimized the salt reduction process of bacon products through single-factor experiments and orthogonal experiments, and the optimal salt reduction scheme was determined to be a marination time of 4 days, a salt addition of 3%, and a 30% replacement ratio of potassium chloride. Additionally, wheat protein can regulate the impact of potassium chloride substitution for sodium chloride on meat products.

High concentrations of potassium salts impart bitterness, adversely affecting the flavor of meat products, which limits the application of potassium chloride in meat products. Currently, in the processing of low-sodium meat products, flavor modifiers are primarily used for compounding to prevent the occurrence of adverse flavors in products and improve sensory quality. Wang et al. used glycine as a flavor modifier and studied the effects of a compound low-sodium salt comprising sodium chloride, potassium chloride, calcium chloride, and glycine in a ratio of 58:30:7:5 on the quality and flavor of fermented sausages. The results showed that reducing sodium chloride by 42% had no adverse effects on the quality and flavor of the fermented sausages. In addition to sodium intake through sodium chloride, sodium ions can also be ingested through sodium lactate. Sodium lactate is widely used in the food industry for preservation, moisture retention, and flavor enhancement, serving as the second largest source of sodium ions in the human diet. Potassium lactate exhibits similar properties and effects as sodium lactate, thus serving as a non-sodium salt substitute for reducing sodium chloride content. Schivazappa et al. [25] added a mixture of potassium chloride and potassium lactate to meat products, replacing 50% of table salt while ensuring product flavor, demonstrating the feasibility of potassium lactate in the processing of low-sodium meat products.

In addition to the above inorganic salts, organic salts such as sodium citrate, lactate (potassium lactate, calcium lactate), sodium gluconate, calcium ascorbate and so on have also become substitutes for sodium chloride. He et al. [26] applied a compound low-sodium salt containing magnesium chloride in the processing of low-sodium sausages and found that the compound low-sodium salt improved the antioxidant capacity of sausages. Calcium lactate plays a role in antioxidation and color protection in foods and can achieve the purpose of salt reduction when added in compound form to meat products. Zhao found that a calcium chloride to calcium lactate ratio of 2:1 could replace 40% of table salt in pork. Ruusunen et al. [27] discovered that calcium lactate could replace 10% of table salt in ham while effectively preserving the flavor of the ham. While maintaining the original flavor and quality of meat products, the significant reduction of sodium content in meat products using non-sodium salts is an important research direction in the development of low-sodium meat products.

Additionally, the combined use of various salt reduction techniques and non-sodium salt substitution is a feasible approach in the processing of low-sodium meat products.

The technique of salt reduction using flavor enhancers is designed based on the principle of taste multiplication. When two or more stimuli act simultaneously on sensory organs, the resulting sensation exceeds the sum of each stimulus acting alone, a phenomenon known as synergistic effect or summation phenomenon. This phenomenon has been successfully applied in sensory evaluation of foods, new product design and development, and formulation of composite seasonings.

2.3 Processing Technology

2.3.1 High Pressure Processing

High-pressure processing (HPP) technology effectively deactivates microorganisms in food, reducing microbial contamination while preserving the original flavor, texture, and nutritional value of the food product [29]. Alina et al. [28] subjected ham to ultra-high pressure treatment, and the results revealed that high-pressure treatment could reduce the amount of salt used in ham processing and improve its water retention capacity to a certain extent. Picouet et al. [31] found that ham processed by ultra-high pressure had a higher saltiness than untreated ham, and high-pressure treatment also promoted the binding of sodium with proteins. Additionally, HPP technology meets consumers' demands for minimally processed, additive-free products, maintaining sensory and nutritional characteristics, and facilitating the development of low-salt meat products. Several studies have shown that HPP not only optimizes the release of NaCl in the oral cavity but also enhances the perception of saltiness in various meat products by altering the binding forces between NaCl and the product matrix. Yang et al. [30]investigated the effects of high pressure on cooking loss and functional properties of low-fat, low-salt emulsified sausages, finding that high-pressure treatments at 300 MPa or 400 MPa significantly reduced cooking loss and increased the protein, fat, and moisture content of the sausages. The authors speculate that it may be attributed to the induction and increase in the solubility of myofibrillar proteins, such as myosin, actin, and myosin light chains, as a result of partial depolymerization and unfolding, which, in turn, contributes to the formation of a more stable gel matrix. Tintchev et al. [32] also reported that this gel matrix exhibited greater water-holding capacity and fat-binding ability in the protein network of cooked sausages. Studies have shown that low-salt beef emulsified sausages processed with high pressure exhibit favorable sensory scores, texture properties, and water retention.

However, excessive pressure may result in product hardening, as different pressures can induce varying degrees of structural rearrangement in water, lipids, and proteins, thereby affecting the sensory and nutritional value of the food. Therefore, when applying HPP processing to low-salt meat products, it is essential to consider the potential adverse effects of excessive pressure.

2.3.2 Ultrasound

Ultrasound technology, as a salt reduction technique in food processing, operates on the principle that ultrasound can disrupt the structure of myofibrils, increase the spacing between fibers, and enhance the dissociation of myosin, creating channels that accelerate the flow rate of sodium ions during salting. This mechanism rapidly establishes an equilibrium state between the saltwater and meat tissue concentration gradients, thereby preventing salt accumulation on the surface of the meat [33]. Research on meat products has demonstrated that ultrasound effects yield desirable outcomes without compromising the quality of meat products [34]. Barreto et al. [35], to investigate the impact of ultrasound on the quality of low-salt restructured ham, produced four types of low-salt restructured ham (1.5%, 1.12%, 0.75%, and 0.75% salt + ultrasound) and evaluated them based on physicochemical properties, total fluid release (TFR), color, thiobarbituric acid reactive substances (TBARS) value, microbial indicators, microstructure, and sensory evaluation. The results showed that ultrasound application improved the physicochemical properties of restructured cooked ham, reducing total fluid release, increasing yield, improving color, and had no adverse effects on oxidative stability, while reducing salt content by 50% and sodium content by 32%. Ultrasound induced microfissures in muscle fibers, altering the microstructure of restructured cooked ham, thereby enhancing sensory acceptance of taste and texture parameters as well as overall acceptability. Pan et al. [36] produced low-salt bacon with a NaCl content of 15% (traditional bacon ranges from 6% to 8%) using vacuum rolling combined with ultrasound-assisted technology, with shorter curing time. Shao et al. [37] found that ultrasonic treatment disrupts muscle fibers, enhances mass transfer efficiency, and enables rapid and uniform diffusion of sodium chloride into the tissue, expediting the marination process. Deng et al. [38] observed that high-power ultrasonic-assisted treatment improves the mass transfer efficiency of salt, hastening salt penetration. Ultrasonic treatment has a positive impact on the flavor formation of meat products. Zou et al. [34] subjected sauce beef to ultrasonic treatment, inducing cavitation effects that significantly accelerate sodium chloride penetration and lead to increased production of sugars and nucleotides, while also promoting lipid oxidation in sauce beef, resulting in a significant increase in the types and relative contents of volatile flavor compounds.

The high-power ultrasound can cause damage to muscle tissue, resulting in loose and less compact muscle fibers. It was also observed that there was an increase in hardness after applying high-power ultrasound(1000 W) to the steak. However, another study by Yeung et al. [40] found that ultrasound reduced the stiffness of pork tenderloin. The author contends that high-intensity ultrasound treatment can enhance the cohesiveness and hardness of low-salt meat products, thereby improving their palatability and consumer acceptance. According to an unpublished manuscript by the author, ultrasound (650W) can alter the structure of myoglobin, weakening its binding with catechins, thereby enhancing the antibacterial effect of catechins. But different meats have distinct compositions; for instance, chicken meat contains less connective tissue compared to beef. Therefore, it is crucial to avoid excessive ultrasound treatment in terms of both power and duration to prevent undesired increases in hardness, which could adversely affect the texture and decrease consumer acceptance.Therefore, continual optimization is necessary to explore an appropriate low-salt assisted processing technique using ultrasonic waves without affecting the state of muscle fibers.

2.3.3 *Pulsed Electric Field*

Pulsed electric field (PEF) technology can influence the diffusion, distribution, and release of sodium ions in meat matrix by inducing electroporation and increasing cell membrane permeability. This effect may alter the interactions between proteins and salt ions and affect the release of sodium ions during chewing [39]. Bhat et al. [41], to evaluate the salt reduction effect of PEF in meat products, prepared two batches of low-salt beef jerky with NaCl content of 1.2% (one batch treated with PEF) using 2.0% NaCl beef jerky as control, and assessed their physicochemical characteristics and sensory attributes. The results indicated that PEF significantly influenced the shear force and toughness of the products ($p<0.05$) but had no adverse effects on product color, lipid oxidation, and microbial stability. The sodium content of samples treated with PEF was significantly lower than that of the control group ($p<0.05$), with sensory scores comparable to the control group ($p>0.05$), and over 84% of expert panelists preferred the saltiness of the PEF-treated samples. Ma et al. [42] analyzed the sensory and texture attributes of lamb meat treated with PEF technology, revealing that high-pressure pulsed treatment not only improved the sensory attributes but also positively impacted the juiciness of lamb meat. Therefore, PEF technology, by affecting salt diffusion and sodium transport, can improve saltiness perception during chewing and represents a salt reduction processing technique with considerable potential for application.

2.4 Flavor Enhancer

2.4.1 *Taste Peptides and Amino Acids*

Taste peptides refer to a class of small peptide molecules extracted or synthesized from food that possess taste characteristics and can significantly improve the flavor of food. Taste peptides exhibit specific taste effects, including sour peptides, sweet peptides, bitter peptides, salty peptides, and savory peptides. The perception of saltiness by the human body mainly occurs through the selective absorption of sodium ions by sodium ion channels in taste cells to produce a salty taste. Salty peptides can release cations, and these cations pass through sodium ion channels on the surface of taste cells into the interior of taste cells, causing polarization of calcium ions within taste cells, generating currents, and releasing neurotransmitters to form the perception of saltiness [43]. In terms of the perception level of saltiness, some dipeptides containing arginine, such as Arg-Ala and Arg-Pro, can enhance the brain's perception of saltiness [44]. Schindler et al. [45] utilized sensoromics technology to isolate arginine dipeptides from fermented fish disks that enhance salty taste. Salty peptides are primarily composed of amino acids and not only enhance the salty taste of food but also improve the nutritional functionality of products. However, due to the expensive production costs of salty peptides, industrial production and application of salty peptides are rarely reported. Exploring a low-cost, high-efficiency method for synthesizing salty peptides is a direction for future research on salty peptides.

Amino acids are an important taste substance. For instance, when strong flavor enhancers like nucleotides coexist with sodium glutamate and sodium chloride, the umami taste is significantly enhanced, surpassing the sum of umami taste when each seasoning is used alone. Adding an appropriate amount of salt to a sodium glutamate solution can also enhance the umami taste. On the other hand, the flavor of food is often considered as a broader combination of taste and aroma sensations. These two interact during eating, conveying the perceived taste. Adding salt-enhancing aroma compounds to sauces or seasonings can significantly enhance the perception of salty taste in alkaline salt solutions, such as meat flavor. Extracts with salty taste (e.g., seaweed and shellfish aqueous extracts) or stimuli that promote sodium ion channel opening to enhance salty taste perception (e.g., allicin, capsaicin, piperine, and gingerol) can be added to foods to achieve salt reduction [46]. Hunter et al. [47] evaluated the effect of adding 0.5 or 1 μM capsaicin (the main pungent component of chili peppers) to a 75 mM NaCl solution and found that when capsaicin was added to the solution, a significant number of individuals perceived a stronger salty taste. The mechanism behind this salty taste effect may involve capsaicin affecting the metabolic activity of the insula and orbitofrontal cortex (OFC) of the brain, thereby significantly reducing individual salt preferences. Additionally, 2% seedless grape marc can not only prevent microbial spoilage in low-salt beef patties (with salt contents of 2%, 1.5%, and 1%) but also impart fiber, lipid peroxidation, phenolic compounds, and wine flavor to the beef patties, enhancing sensory richness [48]. Yan et al. prepared pea protein hydrolysates and melanoidin reaction products (MRPs) and found through taste analysis that, at the same salt mass concentration, the addition of appropriate MRPs can significantly enhance saltiness and umami taste, with a higher pH resulting in a more pronounced flavor enhancement effect. However, it's worth noting that flavor enhancers may also bring some adverse effects, such as excessive intake of sodium glutamate (>16 mg/kg B.W./d), which may cause health problems including headaches, palpitations, cardiovascular diseases, and gastrointestinal disorders [49].

2.4.2 *Other Substance*

Many substances are incorporated to develop low-sodium meat products, such as spices, polysaccharides, plant extracts, nucleotides, and probiotics. Polysaccharides modify protein structure, enhancing properties such as texture and WHC [2]. Xylooligosaccharide and yeast extracts synergistically improve rheological, physical, and organoleptic attributes while reducing bitterness [50]. Incorporating locust bean gum, potato starch, and kappa-carrageenan enhances sausage qualities Sea ponzu, kelp, and wolfberry extracts effectively reduce sodium chloride content without compromising saltiness [51]. Bisporus mushrooms alleviate flavor deficiencies in low-sodium beef tortillas [52]. Lactic acid bacteria, especially Lactobacillus plantarum and Lactobacillus campestris, enhance flavor, color, and texture in reduced-salt sausages. 5'-Nucleotides like guanosine-phosphate, inosine-phosphate, and adenosine-phosphate act as flavor enhancers by masking bitterness and enhancing saltiness and aroma. Adenosine phosphate mitigates bitterness and boosts saltiness and aroma in low-sodium chicken broth [53].

2.5 Combined Alternative Technology

From the perspective of the multi-factor interaction in hurdle technology, the single substitution of salt often yields suboptimal results, whereas the combination of multiple lower-intensity hurdle factors produces significantly stronger effects(2001). According to the fundamental principles of hurdle technology, water activity (aw) is one of the most critical factors in ensuring food quality, safety, and shelf-life stability (1993). The presence of water is necessary in the process of microbial and enzymatic spoilage of food; the higher the aw, the easier it is for spoilage to occur. Reducing food's aw is a common and effective method for extending shelf life. This can be achieved through drying and dehydration, adding aw regulators, or freezing. Drying and dehydration are the most direct and rapid methods to reduce aw, but excessive moisture removal can lead to overly dry and hard texture in meat products, limiting the extent of dehydration.

Freezing food also reduces aw, for instance, fresh processed meats with an aw of 0.98 can have their aw reduced to 0.95 and 0.75 at temperatures of -18°C and -48°C, respectively, which is effective for frozen storage. For most semi-dry and non-frozen foods, adding aw regulators such as salt, polyphosphates, sodium citrate, ascorbic acid, glucono delta-lactone, sodium acetate, sodium lactate, sucrose, and glucose is the most common method to reduce aw. Among these, salt is the most efficient and safe. For example, adding 3% sodium acetate and sugar to meat products can lower aw by about 0.07, while the same amount of salt can lower aw by 0.2, which is significant for ensuring food safety and storability, effectively inhibiting pathogens such as Staphylococcus aureus, Listeria monocytogenes, and Clostridium botulinum.

Each storable food contains a unique interaction of hurdle factors to ensure balance in microbial and enzymatic stability. A slight change in one hurdle factor (e.g., reducing salt content causing an increase in aw) can negatively impact product safety and overall quality. For instance, emulsified sausages adjust aw to below 0.96 through salt (about 3.0%) and fat (about 30%), while cured and dried products adjust aw to below 0.80 through the addition of salt (4%–5%) and drying (to moisture content below 35%). Seasoned and braised foods adjust aw to below 0.96 through the addition of salt (3%–4%) and sugar (2%–5%) (2014).

In some foods, hurdle factors interact in a synergistic manner, affecting the product's microbial stability and overall quality. Reducing salt lowers the strength of the aw hurdle, altering the interaction with other hurdles such as pH (acid-base adjustment), T (low temperature), F (heat processing), and Eh (deoxygenation), which can collectively impact sensory attributes, flavor, texture, water-holding capacity, and microbial stability. For instance, in industrialized braised pork canned products, the storage conditions at room temperature include: F >0.4, pH <6.5, aw <0.96, and very low Eh (vacuum packaging). Changes in any of these factors can lead to changes in the entire system.

Therefore, in developing low-salt meat products, it is crucial to examine the specific hurdle factors and their interactions for each product. The decrease or elimination of aw hurdle strength due to reduced salt must be compensated for by alternative measures to maintain the balance and effectiveness of the overall system.

3 Effect of Salt Reduction on Storage Characteristics of Meat Products

3.1 Physical Characteristics

Salt plays a crucial role in improving the texture and water-holding capacity of meat products, while also positively impacting their color. Therefore, reducing salt content may adversely affect the texture, water-holding capacity, and water activity (aw) of meat products [54]. Research by Bower et al. [66] found that reducing salt content in turkey and beef adversely affects hardness, adhesiveness, and cooking yield during storage. Similarly, Cluff et al. [55] demonstrated that reducing salt content in pork sausages may significantly increase hardness during storage. Bampi et al. [56] observed that substituting 25% of sodium chloride with potassium chloride in beef resulted in a faster diffusion rate of potassium chloride during the curing process, with a smaller decrease in aw in beef. Therefore, reducing salt content in meat products may lead to deterioration in certain physical qualities during storage.

3.2 Chemical Characteristics

Current research suggests that sodium chloride (NaCl) in meat products may act as both a pro-oxidant and an antioxidant [57]. Rhee et al. [58] found that lower concentrations of salt in pork promote lipid oxidation, while concentrations greater than 2% inhibit lipid oxidation, which is consistent with the findings of Sharedeh et al. [59]. However, Wu et al. [61] found significant effects on protein and lipid oxidation in dry-cured bacon when the substitution ratio of potassium chloride exceeded 40%, which contradicts the conclusions of Hernández et al. [62] Although sodium chloride can significantly inhibit the activity of glutathione peroxidase, thereby promoting lipid oxidation compared to potassium chloride, this also depends on the ion strength of potassium chloride and sodium chloride and the type of meat product. Santos et al. [60] found that adding calcium chloride promotes lipid oxidation in dry-fermented sausages, consistent with the findings of Flores et al. [64]. However, Horita et al. [63] observed significant inhibition of lipid oxidation in low-fat sausages when using potassium chloride and calcium chloride as substitutes for salt, suggesting that different types of meat products or different antioxidant properties of certain components and additives in meat products may contribute to these discrepancies.

For the author's perspective, these conflicting findings underscore the complexity of the interactions between salt and meat products, as well as the need for further research to elucidate the mechanisms underlying these effects. It is crucial to consider the specific composition and processing methods of different meat products when evaluating the impact of salt on oxidation processes. Additionally, the development of tailored approaches for different meat products may be necessary to optimize their storage properties while minimizing the risk of oxidation-related deterioration.

3.3 Microorganisms Characteristics

3.3.1 Spoilage Bacteria

Salt can suppress the growth of harmful microorganisms and extend the shelf life of meat products by reducing their water activity (aw). Research by Martinez Sepúlvedal [65] has shown that reducing the salt content in cooked sausages can alter the microbial population and affect the shelf life of the product. Bower et al. [66] found that decreasing the salt content during storage led to the growth of lactic acid bacteria in roast beef, with roast beef containing lower salt content (1.5%) having the lowest pH value and the highest lactic acid bacteria count. Similar conclusions were drawn by Zhang et al. [68], where reducing the salt content in Sichuan bacon from 6% to 3% resulted in significant growth of lactic acid bacteria during storage. Harnack et al. [69] discovered that reducing the salt content (from 6% to 3%) in traditional blood sausages in Portugal promoted the growth of mesophilic microorganisms. Aaslyng et al. [67] found that reducing the salt content in hot dogs did not significantly affect the growth of lactic acid bacteria and aerobic microorganisms during storage; however, lowering the salt content in bacon promoted the growth of lactic acid bacteria and aerobic microorganisms during storage, thereby shortening the product's shelf life. Similarly, Delgado-Pando et al. [70] found that reducing salt usage by 34% in bacon and 19% in ham promoted microbial growth. The above research results indicate that the effect of salt content on microbial growth varies among different meat products. Yang et al. [71] found that the growth of aerobic mesophilic bacteria in pork sausages was inhibited when calcium chloride and potassium chloride partially replaced sodium chloride. This is consistent with the findings of [72]: replacing salt in cooked ham with calcium chloride, magnesium chloride, potassium chloride, and magnesium sulfate, it was found that divalent chlorides (especially calcium chloride) exhibited the strongest antibacterial effect. Therefore, reducing the salt content in meat products significantly affects the microbial community structure in these products.

3.3.2 Pathogenic Bacteria

Salt is considered the most effective and widely used antibacterial ingredient in food [73]. Research [74] found that equimolar concentrations of potassium chloride and sodium chloride have similar inhibitory effects on pathogenic bacteria such as Pseudomonas aeruginosa, Escherichia coli, Shigella flexneri, Salmonella enterica, and Staphylococcus aureus. However, Boziaris et al. [75] demonstrated that equimolar concentrations of potassium chloride and sodium chloride in MRS broth had no significant difference in their effects on the growth and reproduction of Listeria monocytogenes, possibly due to their similar physicochemical properties. Some scholars have found that salt and sodium nitrite can synergistically inhibit the growth of Clostridium botulinum in cured meat products, but the interaction between other alternative salts and sodium nitrite has not been studied [77]. Li et al. [76] found that replacing all salt with potassium chloride and potassium lactate in smoked ham promoted the growth of Listeria monocytogenes in the product, reducing its storage stability and microbiological safety. Therefore, reducing the salt content in meat products may lead to the growth of pathogenic bacteria in the product, thereby posing microbiological safety concerns.

3.4 Volatile Flavor Substances

Volatile flavor compounds in meat products mainly originate from the breakdown of fats and the hydrolysis of proteins. Free fatty acids (FFAs) produced from fat breakdown undergo oxidation to generate various volatile compounds, including aldehydes, methyl ketones, and alcohols. Peptides and free amino acids generated from protein hydrolysis through the action of aminopeptidases form free amino acids (FAAs). Studies have shown that the salt content can influence the activity of some endogenous enzymes in meat, thereby altering the extent of fat breakdown. Conversely, reducing salt content affects the degree of fat oxidation in meat products, thereby significantly impacting the formation of volatile flavor compounds [77, 78]. Wang et al. [79] conducted research on Sichuan bacon with varying salt content and found that higher salt content promoted the formation of flavor compounds in bacon. The use of common metals as salt substitutes also affects the activity of fat-degrading enzymes and alters the composition of FFAs. Additionally, these salt substitutes affect the degree of fat oxidation in meat products. Therefore, the use of these metal salt substitutes affects the formation of volatile flavor compounds in meat products by influencing fat breakdown and fat oxidation [80]. Santos et al. [60] found that adding potassium chloride as a salt substitute did not significantly affect the generation of volatile flavor compounds in dry fermented sausages. However, adding calcium chloride as a salt substitute promoted fat oxidation in dry fermented sausages, facilitating the generation of volatile flavor compounds. Santos et al. [77] also found that adding calcium chloride exacerbated fat oxidation in dry fermented sausages and promoted the formation of some volatile flavor compounds, such as aldehydes and (E)-hept-2-enal. Ojangba et al. [81] discovered that partially substituting salt with potassium chloride in dry-cured ham significantly increased the thiobarbituric acid reactive substances (TBARS) value and unsaturated fatty acid content in the final product, ultimately promoting the generation of volatile compounds during storage, including ethanol, sulfides, and alkanes. Lowering the salt content in meat products may lead to a decrease in volatile flavor compounds during storage, while the use of certain salt substitutes may promote fat hydrolysis and oxidation, thereby facilitating the formation of volatile compounds in meat products.

3.5 Sensory Quality

Salt serves to provide saltiness and enhance the flavor of meat products, while also positively affecting their texture. Therefore, reducing salt content can have a significant negative impact on the sensory quality of meat products. Wu et al. [61] replaced salt with potassium chloride (0-60%) in dry-cured meat products and found that when the replacement ratio of potassium chloride was less than 40%, there was no significant effect on various sensory indicators of the product. Additionally, reducing the salt content in dry-cured meat products to 3.14% did not significantly affect their sensory quality during storage. Campagnol et al. [78] found that when 50% of salt was replaced with potassium chloride in fermented sausages, the sensory quality was inferior. This was attributed to the metallic bitterness generated by replacing 50% of salt with potassium chloride, which also promoted protein hydrolysis and the production of off-flavors during storage. Therefore, reducing salt content in meat products may impact the sensory quality of the final product.

4 Future direction

4.1 Low-temperature Plasma Technology

Plasma technology is increasingly being applied in food processing, particularly in the context of reducing salt content in meat processing. This technology utilizes reactive species such as photoelectrons, ions, and free radicals, generated by the surrounding medium, to inhibit microorganisms in food and degrade chemical pesticides. In meat processing, plasma technology plays a dual role in enhancing meat quality and minimizing salt usage, thus contributing to the production of healthier food options. For instance, low-temperature plasma technology has demonstrated efficacy in degrading pesticide residues while preserving the bactericidal and freshness-retaining properties of food without compromising its quality attributes. Moreover, studies have indicated that the application of plasma technology in treating meat products like cured beef and ready-to-eat ham can substantially reduce microbial populations, thereby enhancing food safety within a specified sterilization duration.

In the realm of aquatic product processing, the traditional method of preservation involves the use of NaCl; however, excessive sodium salt consumption poses health risks. Consequently, researchers are exploring the potential of plasma technology as a means of regulating salt reduction to diminish sodium salt usage while upholding the quality standards of aquatic products.

Low-temperature plasma technology has demonstrated efficacy in eradicating harmful microorganisms in the processing and storage of meat and meat products, thereby extending their shelf life while preserving their flavor, nutrition, and color attributes. This cold sterilization technique offers advantages of safety, cleanliness, and low energy consumption, potentially serving a role in salt reduction in meat processing. However, low-temperature plasma technology is currently in the fundamental research stage and faces several challenges. These include limited penetration capability, significant impact on surface microbial populations, and insufficient bactericidal efficacy within the deeper layers of meat tissue. Hence, integrating this technology with other non-thermal processing techniques may enhance salt reduction outcomes, further improving the safety and shelf life of meat products. As an alternative to salting, plasma technology can be used to treat meat surfaces, thereby potentially reducing the need for salt as a preservative and improving safety by inactivating surface pathogens.

Overall, plasma technology presents significant potential in reducing salt content in meat processing. It not only enhances food safety and freshness but also aids in lowering sodium salt intake, thereby fostering the healthful and sustainable advancement of the food industry.

4.2 Flavor Fusion

Envision artisanal blends of herbs and spices that not only reduce the need for salt but also elevate the sensory experience.

The combination of these ingredients creates a rich, flavorful profile for your dish. Rosemary adds a robust, woodsy aroma with a touch of evergreen essence, while thyme delivers a subtle, dry aroma with a hint of minty flavor that complements the meatiness. Oregano offers an earthy, slightly bitter, and peppery note, enhancing the depth of flavors. Basil provides a sweet, floral element that brightens the overall taste profile. Garlic and onion powders contribute a savory base, with garlic mimicking the umami quality of salt and onion adding a sweet yet sharp complexity. Smoked paprika infuses gentle smokiness, reminiscent of char-grilling, without overpowering. A pinch of cayenne pepper introduces a spicy kick that stimulates the palate, making the dish moreish. Finally, lemon zest brings a zesty, citrus note to cut through the richness and balance the savory spices.

To prepare your herb and spice blend, start by combining the herbs and spices in balanced proportions. Begin with rosemary, thyme, and oregano as the base, and adjust the levels of garlic and onion powder according to your preference, ensuring they do not overpower the fresh herbs. Next, use a mortar and pestle or a spice grinder to grind the ingredients into a fine, even powder. Allow the blend to sit in an airtight container for a few days so the flavors can meld and intensify. When you're ready to cook, generously rub the blend onto the meat, allowing time for the meat to absorb the rich flavors.

This artisanal blend, "Savory Symphony," aims to reduce sodium intake without sacrificing flavor. The combination of these herbs and spices is designed to complement the natural taste of meat, providing a rich and aromatic experience that makes the dish satisfying and memorable.

4.3 Technology Twist

Advanced processing techniques like vacuum tumbling and ultrasonic marination represent innovative approaches to meat processing that can significantly enhance flavor penetration and distribution. Here's how they work:

Vacuum tumbling and ultrasonic marination are two innovative techniques that enhance the marination process for meat. In vacuum tumbling, meat is placed in a rotating drum from which air has been removed, creating a vacuum. This process opens up the meat's fibers, allowing the marinade to penetrate more deeply, resulting in improved flavor uptake, more uniform distribution, and tenderization. This efficient infusion of flavors can reduce the need for salt. Ultrasonic marination employs high-frequency waves to create microscopic channels in the meat, allowing the marinade to penetrate quickly and evenly. This leads to faster marination times, enhanced flavor absorption, and even distribution of the marinade throughout the meat, potentially reducing salt usage. Both techniques are designed to maximize flavor while minimizing the need for high levels of salt, making them ideal for creating healthier yet flavorful meat products. By employing these methods, producers can offer meat that is not only lower in sodium but also rich in taste, satisfying consumer demand for healthier options without compromising on flavor.

4.4 Consumer Education

Creating campaigns that both inform and excite consumers about the benefits of reduced-salt products can be a powerful way to encourage healthier eating habits. Here's a concept for such a campaign:

The campaign incorporates various elements to promote low-sodium living and healthy eating habits. Interactive workshops feature cooking classes led by skilled chefs who teach participants how to use herbs and spices to enhance flavor in low-sodium dishes. Social media challenges, such as the Low-Salt-Lifestyle challenge, invite individuals to share their own recipes and tips, with prizes awarded for the most creative and delicious dishes. Partnerships with influencers help raise awareness of the flavorful potential of low-salt foods and encourage followers to adopt healthier habits.

Educational content, including infographics and videos, showcases the health benefits of reducing salt intake, such as lowering blood pressure and reducing the risk of heart disease. Taste test pop-ups in busy areas provide opportunities for people to sample low-salt products and experience firsthand that less salt does not mean less flavor. Storytelling ads share personal stories of individuals who have improved their health through a low-salt diet.

An app designed to help consumers track their daily salt intake and suggest low-salt alternatives for favorite foods can make the transition easier. Additionally, partnerships with health organizations such as the WHO ensure the campaign aligns with global efforts to reduce sodium intake and protect lives. The goal of this campaign is to shift the perception of low-salt diets from one of deprivation to one of discovery, making the choice for health a delightful and enriching experience. By focusing on the positive aspects of flavor and well-being, the campaign aims to inspire a movement towards mindful, enjoyable eating.

4.5 Sustainability Synergy

The use of locally sourced, sustainable salt alternatives is a commendable approach that supports both community health and environmental sustainability. Here are some considerations for such practices:

Encouraging the cultivation of local herb gardens provides fresh and flavorful alternatives to salt, such as rosemary, thyme, and basil, enhancing food taste naturally. Partnering with Community Supported Agriculture (CSA) initiatives ensures the community receives locally grown produce, including herbs and spices that serve as salt substitutes. Educational programs and workshops teach community members about the health benefits of reducing salt intake and how to use local herbs and spices in cooking. Supporting farmers' markets allows residents to purchase locally sourced, low-sodium products and learn about sustainable farming practices. In coastal areas, sustainable salt harvesting methods, such as solar evaporation ponds, minimize environmental impact and produce natural sea salt. Salt reduction campaigns emphasize the benefits of local, sustainable salt alternatives for health and the environment.

By focusing on these areas, communities can develop a more sustainable and health-conscious food culture that values local resources and the well-being of the environment.

5 Conclusion

The reduction of salt content in processed meats is a complex challenge due to the multifaceted roles of sodium chloride in meat processing and the significant impact of excessive sodium intake on global health Various strategies have been explored to address this issue, including the use of additives like sodium nitrite, low temperature, and pH regulation to ensure product safety and stability. Improving the water-holding capacity of meat products through the interaction of salt with meat proteins is crucial for maintaining quality and enhancing sensory characteristics. Technologies such as pulsed electric field (PEF) have shown promise in reducing salt content while maintaining product quality and sensory attributes. Altering the physical structure of salt, such as using 3D printing technology or micronization, can help control salt distribution and enhance saltiness perception without compromising taste. Overall, ongoing research and innovation in salt reduction technologies are essential to meet the global health targets and consumer demands for healthier processed meat products.

Conflicts of Interest

The author declare no conflicts of interest.

Funding

This work was supported without any funding.

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