Sodium reduction in foods: Challenges and strategies for technical solutions

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Sodium reduction in foods: Challenges and strategies for technical solutions

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Abstract

In many parts of the world, sodium consumption is higher than recommended levels, representing one of the most important food-related health challenges and leading to considerable economical costs for society. Therefore, there is a need to find technical solutions for sodium reduction that can be implemented by food producers and within food services. The aims of this review are to discuss the barriers related to sodium reduction and to highlight a variety of technical solutions. The barriers relate to consumer perception, microbiology, processing, and physicochemistry. Existing technical solutions include inhomogeneous salt distribution, coated salt particles, changing particle sizes and forms, surface coating, multisensory combinations, sodium replacements, double emulsions, adapted serum release by microstructure design, and adapted brittleness by microstructure design. These solutions, their implementation and the associated challenges, and applicable product categories are described. Some of these solutions are ready for use or are in their early development stages. Many solutions are promising, but in most cases, some form of adaptation or optimization is needed before application in specific products, and care must always be taken to ensure food safety. For instance, further research and innovation are required in the dynamic evolution of saltiness perception, consumer acceptance, the binding and migration of sodium, juiciness, microbiological safety, and the timing of salt addition during processing. Once implemented, these solutions will undoubtedly support food producers and food services in reducing sodium content and extend the application of the solutions to different foods.

KEYWORDS

food, inhomogeneous salt distribution, multisensory, safety, sodium reduction, technical solutions

1 INTRODUCTION

Excessive sodium intake increases the risk for high blood pressure and, in turn, cardiovascular diseases, stroke, and other serious diseases. High sodium intake is a leading dietary risk factor for non-communicable diseases globally, measured both in terms of disability-adjusted life years and mortality rates over the last several decades. The World Health Organization (WHO) has reported 10.4 million deaths globally per annum on average as a consequence of high blood pressure (GBD 2017 Risk Factor Collaborators, 2018). Prevention of early deaths by reducing sodium intake could save vast amounts of healthcare-related costs (Levy & Tedstone, 2017).

Average sodium intake considerably exceeds WHO recommendations in many parts of the world (EFSA Panel on Nutrition,Novel Foods and Food Allergens, 2019; WHO, 2012). Estimates show that approximately 70%–75% of sodium intake comes from food produced either by food companies (products such as bread, cheese, meat and processed meat products, ready meals, soups, and sauces) or food services (Harnack et al., 2017). The remainder originates from sodium inherent in raw materials and salt added during cooking at home and at the table. Consequently, WHO and other authorities worldwide have issued distinct recommendations for sodium reduction (EFSA Panel on Nutrition, Novel Foods and Food Allergens, 2019; National Academies of Sciences, Eng & Medicine, 2019). Most countries recommend sodium intake limits of 2.0–2.4 g per day and provide dietary guidelines which suggest reducing sodium intake by choosing food with less salt. Many countries around the world and the European Union's member states have adopted national strategies to reduce sodium intake in the population (Kloss et al., 2015; Santos et al., 2021; Trieu et al., 2015). Most strategies take a broad approach, including reformulation of products, goals for maximum sodium content in specific product categories, reduction of sodium by stealth, information campaigns for increased awareness and education of the population, labeling legislation, and/or imposing taxes on products with a high sodium content. Finland and the United Kingdom are examples of countries where consistent long-term work has resulted in reduced sodium consumption. Finland implemented labeling legislation on sodium content and the United Kingdom introduced maximum targets for salt (sodium chloride) levels in different food categories (He et al., 2014; Pietinen et al., 2008).

In countries where salting is traditionally the main food preservation method, consumers are often accustomed to high salt levels in food which, in turn, affects their taste preferences. Thus, from a long-term perspective, it is desirable to influence the taste preference of the population toward lower-sodium foods. Here, too, increased awareness of the population's preferences and habits is important and must go hand in hand with technical solutions.

To meet the demands from both authorities and consumers, and thereby become competitive in national and international markets, there is a strong need in the food industry to be able to offer products with lower sodium levels. However, there are several challenges associated with sodium reduction in food. Sodium chloride (NaCl) is widely used as an ingredient in many products and fulfills many important functions in foods, including contributing to structure formation, microbial safety, shelf-life, processability, and sensory characteristics. Reductions in sodium content must be done in a manner that does not negatively impact these parameters.

A compilation of interventions made from 2018 shows that there is considerable potential to reduce the amount of sodium in foods, given the right formulations and processes (Allison & Fouladkhah, 2018). However, many of the suggested methods are product-specific and are often kept confidential, and many small and medium-sized enterprises may lack the resources and/or expertise to develop or implement such solutions. There is therefore a need to raise the level of knowledge about different solutions for sodium reduction to enable wider-spread implementations. By joining forces in industrial networks and projects, these food companies can be better equipped.

To help consumers reduce their sodium intake to recommended levels, it is essential that the food industry and food services actively engage in lowering sodium in food products/meals. In addition, authorities and other actors must contribute with information to raise awareness of the need to reduce sodium intake. Collaboration between many actors in society is necessary to achieve this at a population level, where government plays a pivotal role in stimulating cooperation between the private and public sectors (Figure 1).

In Section 2, the reasons that reducing the sodium content in foods is challenging are presented. These include issues regarding sensory perception, food safety, and processing. Subsequent sections will cover technical and multisensory solutions to decrease the sodium content in foods. Finally, general guidelines for sodium reduction and an outlook of future research challenges are provided.

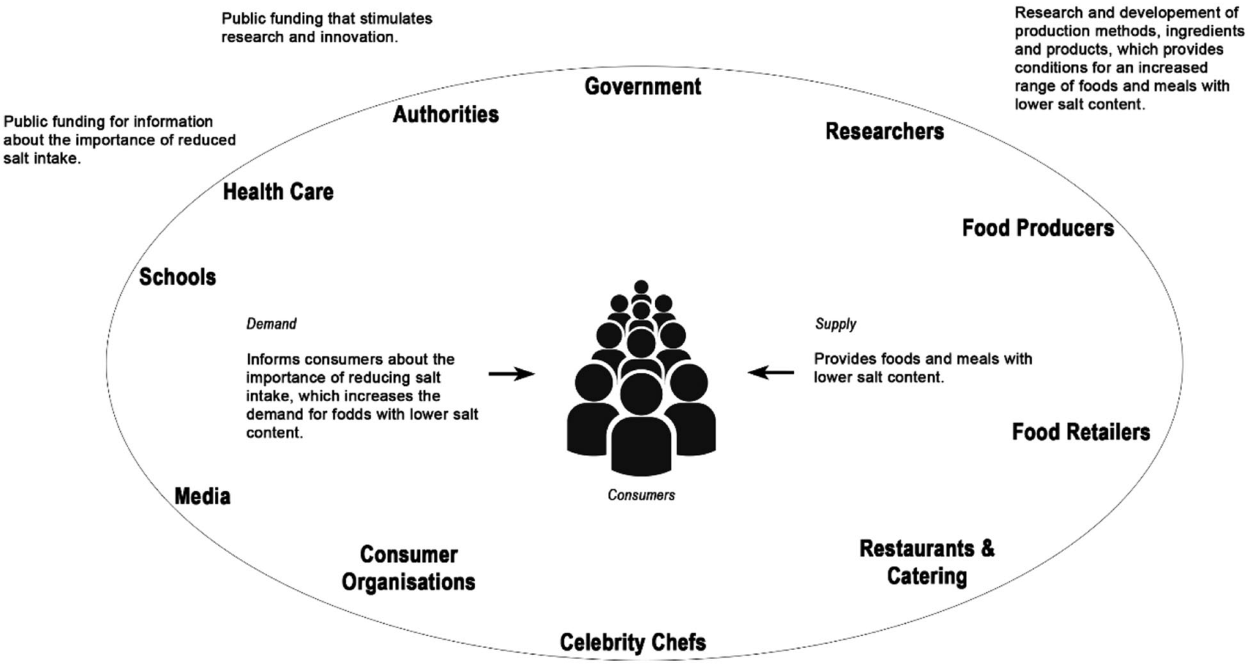

FIGURE 1 Illustration showing the societal infrastructure that is needed to achieve a general sodium reduction at population level

2 | CHALLENGES WITH REDUCING SODIUM CONTENT IN FOODS

2.1 | Perceptual challenges

The act of removing sodium from foods will have consequences for their sensory properties. It goes without saying that reducing sodium will decrease perceived saltiness, which can make the food taste bland and impact the overall palatability. Further, other aspects of flavor such as bitterness may become more noticeable as NaCl is a known bitterness suppressor (Breslin & Beauchamp, 1997). This is a significant concern in foods where bitterness might present itself as replacement salts such as potassium chloride (KCl) do not suppress bitterness as effectively as NaCl (Wise et al., 2019). Sodium reduction can also alter structure formation of food during processing (Rysová & Šmídová, 2021), thereby influencing perceived texture (see section 2.3 for mechanisms). At the individual-level, sodium reduction can also impact consumer responses: each consumer will reach their own optimum preference as a function of sodium content (Jinap et al., 2016). As such, no single salt concentration is universally preferred, and consumers who have high-salt-preferences are more likely to engage in higher sodium intake behavior. Overall, sodium reduction in products that must cater to a wide consumer base while maintaining palatability is therefore a challenging task.

2.2 | Microbiological challenges

Microbial safety of most foods relies on combining preservative factors (hurdles) to produce high-quality food products without compromising on food safety, as a single hurdle is typically insufficient to prevent microbial growth. The most important hurdles are temperature, pH, water activity (aw; i.e., the water available for microbial growth), modified atmosphere, and preservatives (Leistner, 2000). Because NaCl is another hurdle for microbial growth in foods, reductions in NaCl levels must be compensated for by including other or adjusting existing hurdles to maintain microbial safety (Adams et al., 2016).

Microbial growth is dependent on the aw of food, such that the absence of enough water will reduce both microbial growth and the production of unwanted toxic compounds. Reduction of aw does not kill the microorganisms; however, they can remain dormant as spores until better growth conditions are available. Techniques employed to lower the aw and reduce microbial activity in food include drying, freeze drying, and adding salt and/or sugar. Although both sugars and salts bind water and, in turn, lower the aw, salt is more effective. Most bacteria, including several well-known food-borne pathogens and bacteria related to food spoilage microorganisms, are limited to growth at aw levels between 1 and 0.95 (Figure 2), while yeasts and molds are more tolerant and can grow at lower aw levels of ~0.7 (Adams et al., 2016).

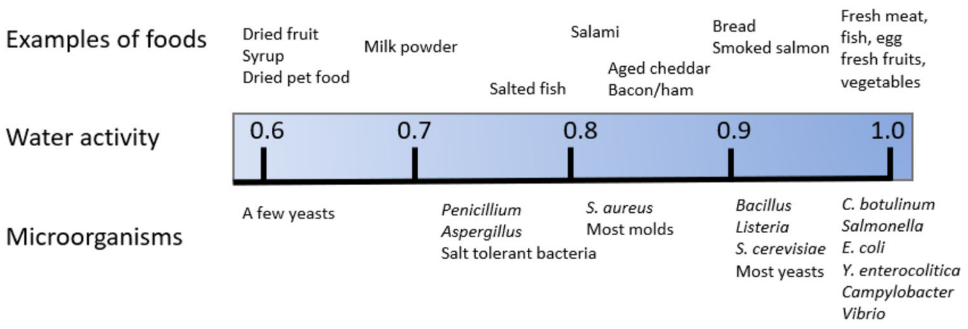

FIGURE 2 Water activity in food products and lowest water activity for growth during otherwise optimal conditions for pathogenic microorganisms

TABLE 1 Microbial challenges and possible solutions in food when reducing sodium

Food	Role of sodium	Relevance	Options when reducing NaCl	References
Cheese	Taste, enzymatic and microbial activities	Contributes to sodium intake, 2% (w/w)	Replace NaCl with KCl, change of lactic acid bacteria and coagulant	(Kastberg Møller et al., 2013; Wemmenhove et al., 2016)
Meat	Taste, inhibits microbial growth	Rich in nutrients, several pathogens associated with meat products.	Heating, freezing, cold storage, canning, vacuum packing, modified atmosphere, fermentation, low pH, use of preservatives	(Aaslyng et al., 2014; Desmond, 2006; Fougy et al., 2016; Glass et al., 1992)
Fish	Preservation in pickled herring marinades	Rich in nutrients, high pH, high aw, low carbohydrate content, spoilage microorganisms produce off-flavors	Heating, freezing, cold storage, canning, fermentation, use of preservatives	(Adams et al., 2016)
Vegetables	Preservation of pickled vegetables	Low sodium content, rich in carbohydrates, and nutrients; have neutral pH, high water content; susceptible to microbial spoilage	Freezing, drying, heat treatment, canning, and fermentation (low pH)	(Adams et al., 2016; Lee, 2004)
Bread	Taste, shelf life, microbial safety	Single largest contributor to dietary sodium intake in US and UK	Replace NaCl with KCl, sour dough bread (low pH), freezing	(Belz et al., 2012; Samapundo et al., 2010)
Sauces, stocks, and salad dressings	Taste, preservation aw	High sodium content, long shelf life, risk of transfer of microorganisms from the consumer into the packages, risk of microbial growth since the packages are repeatedly removed from refrigeration	Cold storage, use of preservatives, glutamate	(Allison & Fouladkhah, 2018)

Reduction of sodium in a food product requires a case-by-case re-evaluation of microbial safety (Table 1). Compensation strategies might influence product quality and appearance differently in different products. At the same time, consumers want clean labels, short ingredient lists, and an extended shelf life. This requires maintenance of a delicate balance, satisfying all aspects from food safety to consumer appeal but safety must come first.

2.3 | Processing and physicochemical challenges

Salt affects the physiochemical properties of food products and serves as an important ingredient for numerous reasons (Dunteman et al., 2022; Rysová & Šmídová, 2021). Consequently, sodium reduction affects aspects beyond flavor and microbiological safety such as structure and texture. In meat products, for example, salt solubilizes the myofibrillar meat proteins, which increases their water- and fat- holding capability. This promotes gel formation and emulsification, in turn, affecting perceived hardness and juiciness. Reduced salt can lead to decreased protein solubility and poorer water holding capacity, and consequently to reduced perceived juiciness (Gaudette et al., 2019; Rios-Mera et al., 2020).

In bread dough, salt decreases repulsive forces in the charged amino acids of the gluten proteins to form stronger interactions through beta-sheets and fibrillar structures (Bernklau et al., 2017). In doing so, the hydrated gluten network forms stronger matrices that can hold starch granules, fibers, and gas bubbles. Sodium also influences proofing time, dough elasticity and extensibility, and the amount of free water (Diler et al., 2016; Dunteman et al., 2021). The ability of salt ions to change the surface charge of proteins is also important for the stability of emulsion-based foods, where proteins act as emulsifiers at the interface of oil and water surfaces. For example, salt strengthens the surface layer of oil droplets in mayonnaise (Depree & Savage, 2001). In the dispersed aqueous phase of water in oil emulsions, salt can also prevent Ostwald ripening with time. This occurs because its presence creates a pressure differential between the inside and outside of the emulsion droplets (Laplace pressures), by lowering the total pressure, leading to reduced diffusion of water from smaller to larger droplets (Zhu et al., 2019).

3 | MULTISENSORY AND TECHNICAL SOLUTIONS FOR SODIUM REDUCTION

In this section, different solutions for sodium reduction are reviewed. They include multisensory combinations, inhomogeneous salt distribution, double emulsions, and salt replacers (Dunteman et al., 2022; Sun et al., 2021; Vinitha et al., 2022).

3.1 | Multisensory combinations to influence salt perception

3.1.1 | Intra-modal interactions (taste-taste)

The influence of perceptual combinations on saltiness perception has received much attention (Shen et al., 2022). Early studies focused on binary mixtures of single taste stimuli with characters of sweet, salty, sour, and bitter and their influence on the sensory perception of each other through intra-modal interactions. As a generic effect, mixtures of tastes at concentrations above perceptual thresholds result in a decrease in target taste intensity, known as mixture suppression (Breslin, 1996), but the extent of suppression is concentration-dependent. Sweet stimuli at medium and high concentrations can suppress the perceived saltiness intensity of NaCl while sour stimuli at low and medium concentrations or even at detection thresholds can enhance perceived saltiness (Keast & Breslin, 2003).

Umami is a key taste that enhances perceived saltiness in basic taste mixtures at suprathreshold levels. Compounds such as monosodium glutamate (MSG) and calcium diglutamate can enhance perceived saltiness of NaCl (Ball et al., 2002; Hayabuchi et al., 2020) and can therefore be used to replace NaCl with minimal impact on perceived saltiness, at least to an extent. The complementary effects of MSG and NaCl on the perception of each other have also been demonstrated in complex taste mixtures of five basic tastes (Niimi et al., 2014b). Umami also extends the duration of enhanced saltiness perception (Kawasaki et al., 2016). These studies indicate that not all tastes have an equal impact on perceived saltiness by enhancement or suppression, and that these effects are not necessarily linearly related to stimulus concentration.

3.1.2 | Cross-modal interactions

Perceived saltiness can also be modulated by aroma sensory stimuli, an example of cross-modal sensory interactions where senses that are physiologically separate can influence each other. Enhancement of perceived saltiness by various aroma characteristics has been reported, particularly by congruent combinations of the salt taste and aromas of savory foods (Seo et al., 2013). This has been demonstrated with food flavors/aromas (for a review, See Thomas-Danguin et al. (2019)), single volatile compounds (Manabe et al., 2020; Zhou et al., 2021), or a model aroma with mixtures of volatile compounds (Lopez et al., 2019), and can even extend to the enhancement of perceived salty after-taste (Ogasawara et al., 2016). Enhancements of flavor perception and saltiness can occur in complex taste mixtures together with aroma (Nasri et al., 2013; Niimi et al., 2014a).

Increases in perceived saltiness are frequently reported when comparing the taste with and without aroma, but the magnitude of enhancement plateaus when aroma concentration reaches a certain level. For example, combining 20 mM NaCl (1.2 g/l) with sardine aroma (0.25 g/l) in solution led to enhanced saltiness perception compared 20 mM NaCl alone, but higher aroma concentrations (> 0.5 g/l) did not provide further enhancement (Nasri et al., 2013). However, contrasting findings of the lack of saltiness enhancement have also been reported, such as with chicken flavor or soy sauce flavor (Linscott & Lim, 2016), dried bonito stock (Manabe et al., 2014), or a model cheese aroma (Niimi et al., 2014a). Most of the studies cited here attribute the saltiness enhancement by aromas to the congruous combination of the two stimuli. The mediator in this case is the extent to which one is familiar with the taste/aroma combination. Thus, for successful enhancements to occur, the presence of highly familiar aroma characteristics with saltiness seems necessary, otherwise the enhancements are less likely to occur.

Chemesthesis (irritation) perception can potentially influence perceived saltiness to some extent, although the literature on this topic is limited. Pungency from Sichuan pepper oleoresins can enhance perceived saltiness both at and below recognition thresholds of NaCl, though enhancement was found dependent on the panelists' sensitivity to NaCl and the pungency of the Sichuan (L.-L. Zhang et al., 2020; Q. B. Zhang et al., 2020). Thus, individual differences in perceptual sensitivity may play a role in whether such enhancements are experimentally detectable or not. Studies on the impact of capsaicin's burning sensation on perceived saltiness have however been limited, contradictory, and inconclusive. Some report saltiness suppression (Prescott et al., 1993), while others report minor enhancement (Narukawa et al., 2011). This is perhaps due to the difficulty in studying the perception of burning itself, as the perception duration is long and could cause confusion in the perception of other gustatory sensations when the stimulus that causes burning is present in mixtures with other stimuli, as well as differences in individual sensitivity. Dissolved CO_2 also influences saltiness perception of NaCl, providing suppression at 0.7 mM (Cowart, 1998) but enhancement at 0.1 and 0.2 mM (Cometto-Muñiz et al., 1987), demonstrating again that saltiness enhancement/suppression appears to be concentration-dependent.

Cross-modal interactions between texture and chemosensory stimuli are challenging to investigate due to measurements being easily confounded by physicochemical, psychological, and physiological influences (Poinot et al., 2013). Nonetheless, other sensory modalities could also affect the perceived saltiness of foods. It has been suggested that haptic cues could influence perceived saltiness, whereby holding a rough-surfaced cup in one hand while consuming potato chips increased perceived saltiness more than while holding a smooth-surfaced cup (van Rompay & Groothedde, 2019). The mechanisms underlying this effect do not currently have any firm explanations, and further examinations of such cross-modal effects are required. However, this result provides a glimpse into the possible way other senses could influence taste/flavor perception and oral somatosensation during consumption.

3.1.3 | Sensory interactions in food systems

The studies described above were conducted mostly in model systems, but the effects also translate to complex everyday foods. For example, replacing table salt with soy sauce reduced the overall NaCl content by 0.2%–0.25% (w/w) in three different product categories (salad dressing, soup, and stir-fried pork) without compromising perceived saltiness intensity (Kremer et al., 2009). In soups, the addition of aroma as compensation led to 15% NaCl reduction, 30% NaCl reduction with the combined use of NH_4Cl with KCl, and aroma in bouillion (Batenburg & van der Velden, 2011), and between 30% and 40% NaCl reduction using MSG (Jinap et al., 2016; Leong et al., 2016). Rubemamine or rubescenamine can also enhance perceived saltiness, and other attributes, in beef extracts (Backes et al., 2015). These studies exemplify the application of taste-taste interactions in real foods and demonstrate the usefulness of this principle even in complex mixtures. Herbs are another promising alternative to compensate for reduced NaCl levels in soups whilst maintaining sensory acceptability (Ghawi et al., 2014; Taladrid et al., 2020; Wang et al., 2014). This is an example of cross-modal taste-aroma interactions, where the aromas of herbs perceptually interact with salty taste.

A few studies have investigated sensory interactions in solid food matrices. For example, reduction of NaCl with unchanged saltiness perception was achieved in pork patties by adding MSG (Chun et al., 2014). In a snack product, perceived saltiness was enhanced by heterogenous layering of both salt and ham aroma (Emorine et al., 2015). However, the extent to which saltiness enhancement was cross-modally driven remains unclear, as the authors did not measure matching control samples. In roast vegetables, a reduction of NaCl and addition of MSG resulted in similar taste for just about right (JAR) distribution between standard NaCl and reduced salt+MSG (Halim et al., 2020). The use of herbs also led to enhanced saltiness perception of a chicken pasta meal with 25% of the original salt content (Barnett et al., 2019).

The literature shows that combinations of stimuli in binary mixtures (intra- and cross-modal) can result in enhancements of saltiness, but only to a limited extent when used in isolation. The most practical and effective means of achieving strong saltiness enhancement seems to be by manipulating multiple components simultaneously, thereby influencing multiple modalities in a complex mixture. Several studies have reported effective salt reduction by means of multisensory combinations in liquid food products such as soups and condiments. The same principle could theoretically be applied in solid food products; however further work is required to address the challenges associated with the physicochemical effects that could confound multisensory measurements. The number of studies that have investigated the impact of multisensory combinations on perceived saltiness in solid foods is limited in comparison to the number of liquid food products, implying an untapped potential in this domain.

3.2 | Sodium reduction by controlling the microstructure

Perceived saltiness is partly dependent on the composition and matrix of the product. Foods such as cheeses, sauces, and condiments have similar sodium concentrations to salty seawater (around 1000 mg sodium/100 g), yet the perceived saltiness is different from seawater due to the impact of the food matrix. Salt perception in food requires that NaCl is dissolved in either solution or saliva and transported to the salt taste receptors (Guo, 2021). The viscosity of solvents or saliva or in-mouth mixture can affect the salt transport rate. Salt dissolution depends on physical characteristics such as surface area, as well as the size and shape of the salt crystals. The microstructure of the food also plays an important role in dissolution (and the resulting perception) and should be carefully considered when developing strategies for sodium reduction. The food microstructure can, for example, form barriers to salt transport, bind the sodium, or influence the break down properties of the food matrix. The manner in which salt is added to the product also matters: there is a large difference between on-surface salt (e.g., savory snacks) and salt incorporated within the product (e.g., bakery products, soups, and sausages).

3.2.1 | Juiciness, brittleness, and sodium release

Interactions between salt and hydrocolloids (gums) in foods have been studied (Aubert et al., 2016) and have been shown to reduce perceived saltiness. One proposed mechanism is that interactions between the gums and sodium ions reduce their availability for dissolution in saliva. Sodium ion mobility can be reduced in the presence of ionic polysaccharides (such as xanthan and kappa-carrageenan) but not in the presence of non-ionic gums (Rosett et al., 1996). An alternative or complementary explanation is that viscosity affects saltiness directly. When ionic (xanthan) and non-ionic (guar and locust bean) gums were added to soup-like model foods, the saltiness perception was strongly influenced by the low shear viscosity of the fluids, regardless of the gum used (Aubert et al., 2016).

For foods where juiciness is important, serum release during consumption (which increases sodium release) can be used as a means to enhance saltiness perception (Stieger & van de Velde, 2013). This method could provide a versatile approach for products such as processed meats (van de Velde & Adamse, 2013). Stieger (2011) prepared several sausages that varied in serum release by means of adding different polysaccharides and found that sausages with a high serum release under mechanical compression were perceived as juicer and saltier by a sensory panel compared to corresponding variants with a low serum release. Structure and composition may also impact serum release in cheeses. One study showed that serum release and saltiness in processed cheese were enhanced by increased water content but reduced by increased fat content (Phan et al., 2008). The saltiness dependence on structure was, however, difficult to describe as large variations were observed in mastication behavior between the test subjects. This variation is thus important to consider when utilizing serum release as a tool for salt reduction.

The brittleness and hardness of solid and semi-solid food products influence food breakdown, mixing, and release of sodium in the mouth (Busch et al., 2013). A food product that is more brittle (lower strain to fracture) easily breaks down into small fragments or particulates. During this process, fresh surfaces are exposed, resulting in increased sodium release. Thus, food products with higher brittleness may be perceived as saltier. In practice, the change in food structure giving rise to increased brittleness required for sodium reduction might be large. It is also highly dependent on the specific food product, meaning that solutions should be tailored to each application.

3.2.2 | Effect of salt crystal size and shape on salt perception

The size and shape of salt crystals affect their dissolution rate in saliva, which affects transfer efficiency to the taste receptors and, in turn, saltiness perception (Quilaqueo et al., 2015; Rios-Mera et al., 2019; Sun et al., 2021). Hollow, flat, or pyramidal salt crystals have fast dissolution rates, as well as crystal structures that are easily fractionated in the mouth (Quilaqueo & Aguilera, 2015; Quilaqueo et al., 2015). Smaller salt particles also have faster dissolution rates and could offer a cost-effective alternative to selecting specific shapes. It has been reported that the salt content could be reduced by 33% (from 1.5% to 1.0%) in beef burgers by using micronized salt instead of regular salt, without decreasing perceived saltiness (Rios-Mera et al., 2019). However, it is important to consider the dissolution rate of salt within the food matrix. For increased saltiness perception, the salt particles should be solubilized in the saliva instead of being dissociated in the food during processing. In Rios-Mera et al. (2019), part of the micronized salt was mixed into the fat of the burgers, to decrease salt dissolution before consumption.

A reduction of salt crystal size could be used as a tool for salt reduction in snack products where salt is applied on dry surfaces. The crystal size has shown to have an impact on (i) the delivery rate of sodium into the saliva, (ii) the maximum concentration of sodium in the saliva, (iii) the maximum perceived saltiness, and (iv) the saltiness onset time. Smaller crystals gave a faster delivery of sodium and therefore increased perceived saltiness. Although small crystals provided increased peak saltiness intensity, a rapid loss of saltiness after chewing was also observed; an important consideration when selecting a sodium reduction strategy (Freire et al., 2015; Moncada et al., 2015; Rama et al., 2013).

3.2.3 | Sodium reduction by encapsulation

The principle of encapsulating salt (e.g., with fat) relates to preventing dissolution of the salt in the food matrix prior to consumption (Rios-Mera et al., 2021). At the point of consumption, the fat layer is broken during mastication and the salt is released for dissolution in the mouth. However, fat also acts as a barrier to salt mobility in the mouth (Rios-Mera et al., 2021), meaning that mixing salt with fat could also possibly reduce perceived saltiness. Noort et al. (2012) prepared bread using encapsulated salt and suggested that the achieved taste contrast could be successful in reducing the overall salt content of bread, though this approach did come with some limitations. The saltiness perception depends on the size of the encapsulated salt crystals: crystals that were too small did not affect the saltiness, and crystals that were too large resulted in decreased consumer liking due to overly high sensory contrast. Furthermore, replacement of salt with encapsulated salt also affected other properties of the bread, resulting in a denser bread structure with coarse pores and lower bread volume.

The use of salt crystals of various sizes to create taste contrasts has also been evaluated in beef patties (Gaudette et al., 2019). Large salt crystals were encapsulated with palm oil to reduce the dissolution rate. Patties with 0.7% large salt crystals (3 mm) had comparable perceived saltiness to patties with 1.0% table salt. However, less desirable aspects such as cooking loss and shrinkage were enhanced. Similarly, for bread, coatings hindered the effect of salt on food structure properties. Less free salt in the meat matrix decreased myofibrillar protein solubilization and resulted in a less stable food matrix. The authors thus suggested that large salt crystals may be a good strategy for sodium reduction in meat products that are less dependent on salt functionality for structure and texture formation, such as beef burgers, rustic charcuterie sausages, and jerky. If salt encapsulation is to be used as a salt reduction tool, it will be important to find a balance between saltiness and functional properties by considering how salt content affects constituents such as water and proteins. The role of fat or other encapsulation materials on salt mobility and saltiness intensity must also be considered. More details on effects of salt particle size and shape as well as encapsulation on saltiness and technological aspects in meat products are described by Rios-Mera et al. (2021).

3.2.4 | Taste contrast and inhomogeneous salt distribution

Engineering the structure of specific food products to enhance saltiness has been proposed as a key strategy for sodium reduction in many processed foods (Aubert et al., 2016; Cai & Lee, 2020; Diler et al., 2016; Emorine et al., 2013; Gaudette et al., 2019; Kuo & Lee, 2017; Noort et al., 2010, 2012; Stieger & van de Velde, 2013). The taste intensity of food depends partly on the location of tastants in the food matrix. Sensory receptors are contrast detectors, and a pulsatile taste stimulation enhances taste perception (Guilloux et al., 2013). That is, if certain parts of a food product are high in salt and others are low, a reduction of the overall salt content is possible, without a concurrent decrease in perceived saltiness. A suggested explanation for this is that the perceived contrast between a pulse (high salt concentration) and an interval (zero or low salt concentration) gives an overstimulation of the taste property, leading to an overall taste enhancement effect (Burseg et al., 2011; Stieger, 2011).

Taste contrast in food products can be achieved in different ways. One is to incorporate large salt concentrations only in some of the elements of a meal. Selective distribution of salt in chicken pieces instead of in the broth allowed for overall salt reduction while maintaining the saltiness intensity in instant soups (Emorine et al., 2013). Salt can also be added to the surface of products to achieve high local concentrations. Mueller et al. (2016) evaluated this technique for pizza crusts, where 75% of the usual amount of salt was sprayed in an aqueous solution onto one side of the crust before baking, reducing the total salt content of pizza crust by 25% without affecting perceived saltiness.

Another way to achieve taste contrast is to structure the food in layers of different salt concentrations. This approach has previously been applied to bread (Noort et al., 2010; Sinesio et al., 2019). The inhomogeneous salt distribution led to a sodium reduction of approximately 30% while the perceived saltiness, in fact, increased. Note that despite placing salt into different locations in a food matrix during preparation, sodium migrates over time and strives to equilibrate. Many food products are further processed after formulation (e.g., heat treatment) and/or stored before consumption, which could affect the efficacy of taste contrasts. In hot snack products prepared with inhomogeneous salt distribution, it was concluded that subsequent cooking, long-time storage and last-minute reheating promoted sodium migration and loss of heterogeneity (Emorine et al., 2013). It is also important to note that creating layered food products may be challenging in an industrial setting (Gaudette et al., 2019; Noort et al., 2012).

3.3 | Double emulsions

Emulsions are systems that disperse two phases that are insoluble with each other so that the resulting matrix is homogenous. Many food products such as mayonnaise, soups, milk, and dressings are oil-in-water emulsions where the oil phase is stabilized by emulsifiers or particles at the interface. Spreads, on the other hand, are the opposite, that is, water-in-oil emulsions. The concept of emulsions can be extended to have both versions in the form of a double (or duplex) emulsion (Jiménez-Colmenero, 2013; Wang et al., 2021). In double emulsions, droplets are emulsified further within a droplet suspension, which can be water droplets incorporated into the oil droplets, forming a W1/O/W2- emulsion (W1 = inner water phase), or vice versa.

Producing stable double emulsions is challenging due to their inherent thermodynamic instability and the existence of osmotic pressure gradients (Frasch-Melnik, Spyropoulos, et al., 2010; Kumar et al., 2022). The double emulsion structure is easily destabilized because the two emulsifiers tend to diffuse from one interface to the other, which changes the curvature. Osmotic pressure differences between the two aqueous phases cause water to be transported between the phases, creating simple O/W emulsions (Frasch-Melnik, Spyropoulos, et al., 2010). Double emulsions for food applications face two additional challenges: (1) finding a replacement for polyglycerol polyricinoleate (PGPR) as the primary emulsifier in W1/O/W2 formulations as PGPR is allowed as an ingredient in foods only in low amounts, and (2) developing efficient non-destructive second-stage emulsification equipment for large-scale production of double emulsions (Muschiolik & Dickinson, 2017).

For sodium reduction, W1/O/W2- emulsions are the most applicable double emulsions. The principle is to either store away some of the water or to achieve a pulsed delivery (a salt burst). If the oil droplets are similar in size to that of a standard oil-in-water emulsion, sensory properties should essentially remain similar to those of a full-fat product; a benefit of the double emulsion approach (Frasch-Melnik, Spyropoulos, et al., 2010). It is worth mentioning that an increased saltiness perception from oil-in-water emulsions with increasing oil phase volume while maintaining a constant total salt content has been reported (Malone et al., 2003). However, the effect on salt perception of adding more oil decreased at higher oil concentrations, due to the obstruction of salt from reaching the taste receptors by the excessive oil. Sodium reduction may also be achieved by maintaining the salt concentration of the continuous outer W2 water phase that is accessible to the taste receptors (Lad et al., 2012), while the inner W1 water phase is without or with less salt. To obtain a stable and functional double emulsion, the migration of the salt between the two phases must be prevented, perhaps by a barrier of monoglyceride and triglyceride crystals at the interface between the inner water phase and the oil (Frasch-Melnik, Norton, et al., 2010).

Double emulsions can also contribute to sodium reduction via pulsed delivery or salt burst strategies. For example, W1/O/W2 emulsions, where the inner W1 water phase is stabilized by commercially modified octenyl succinic anhydride (OSA)-starch, have been created (Chiu et al., 2015).

3.4 | Replacing sodium

Salt is often added to food products as an ingredient in the form of powder or solution. Thus, from a process perspective, it would be advantageous if these ingredients could be simply substituted with other powders or solutions containing less sodium. One strategy is to replace the sodium chloride with other salts such as potassium chloride (KCl), potassium lactate ($KC_3H_5O_3$), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), and magnesium sulfate ($MgSO_4$). Another strategy is to use salt reducers/replacers such as glycine, fermented wheat protein, yeast extract, seaweed, milk salts, mono-sodium glutamate, nucleotides, or maltodextrin (Inguglia et al., 2017). These substitutes can mimic the role of NaCl in food without affecting the perceived saltiness of the products. However, they all carry different challenges concerning microbiological safety, flavor, taste, water-holding capacity, and interactions with proteins and texture. It has been found that if more than 30% of the NaCl is replaced by potassium chloride, for example, a severe metallic taste and bitterness is induced (Israr et al., 2016). Other aspects may also influence the acceptance of salt replacers in foods with strong traditional ties. Choline addition to bread can be an effective means of salt substitution, in

TABLE 2 List of possible technical solutions to sodium reduction with methods and applicable product categories

Technical solution	Scientific approach	Application	Challenges	Product category	Key references
Inhomogeneous salt distribution	Pulsating salt concentration	Layering, spots with high and low salt content	Salt migration, industrial processing, appropriate geometry	Bread,[c] snacks,[a] pizza,[a] vegetarian burgers[a]	(Noort et al., 2010; Sinesio et al., 2019)
Coated salt particles	Delayed salt release	Add fat-coated salt particles	Few commercial fat-coated particles available	Bread,[b] vegetarian burgers,[a] Snacks[a]	(Noort et al., 2012)
Different particle sizes and forms	Alter salt release rate	Add salt particles with different sizes, porosity, and form	Optimal amount for use and mixtures for specific products.	Snacks,[c] bread[b]	(Rama et al., 2013)
Surface coating	Fast salt release	Add salt powder or salt mixture on the surface of the bread	Appearance, extra processing step, formulation	Bread,[c] snacks,[c] vegetarian burgers[a]	(Mueller et al., 2016)
Multisensory combinations	Sensory interactions	Addition of appropriate ingredients of aroma, herbs, spices, tastes	Aroma stability during processing, congruency of ingredient with saltiness and the product category	Burgers,[c] soup/sauce,[c], beverages,[c] pizza,[b] ready meals,[b] snacks,[b] bread,[a] spices[a]	(Batenburg & van der Velden, 2011; Taladrid et al., 2020; van Rompay & Groothedde, 2019)
Replacing sodium	Exchange part of the sodium chloride	Exchange part of the sodium with potassium or other minerals	Bitterness, microbiological activity, protein interactions, texture, water-holding capacity	Cheese,[c] vegetarian burgers,[c] processed meat,[b] soup/sauce,[b] ready meals,[b] spices,[a] beverages,[a] pizza,[a] bread,[a] snacks[a]	(Inguglia et al., 2017)
Double emulsions	Hiding away water without salt	Create $W_1/O/W_2$- emulsions (with barriers)	Osmotic pressure, stability, finding suitable emulsifiers	Beverages,[a] soup/sauce[a]	(Frasch-Melnik, Spyropoulos et al., 2010; Kumar et al., 2022)
Adapted serum release via microstructure design	Release of liquid phase during mastication	Process adaptation, controlling the microstructure, addition of biopolymers	Salt migration, leaking, and losses	Processed meat,[b] vegetarian burgers,[b] burgers[b]	(Stieger, 2011)
Adapted brittleness via microstructure design	Control the time-dependent particle surface to design the salt release	Control the break-down properties of the food in the mouth via particle size, microstructure, structure adhesion and brittleness	Shelf-life stability due to water uptake that can change the brittleness	Bread,[b] snacks[b]	(Busch et al., 2013)
Processing[d]	Address issues of removing sodium chloride (texture, taste, water holding capacity, microbiological growth, adhesion, etc.)	High pressure, ultrasound, pulsed electric fields, microwaves, etc.	Determining suitable processing techniques for each specific product	Processed meat, bread, beverages, vegetarian burgers, cheese, soup/sauce, spices, ready meals, pizza, snacks	(Inguglia et al., 2017; Parniakov et al., 2020)

[a]Requires further investigation.
[b]Has potential but need further optimization and adaption.
[c]Effective approach for salt reduction.
[d]Not part of the detailed review.

TABLE 3 List of challenges that need to be addressed in future research and development

Multisensory	Structure and texture	Processing
Impact of changes in saltiness due to alterations in formulation on consumer acceptance	Binding of sodium to proteins and polysaccharides that influence the release of salt	Investigate the time for addition of salt in the process, which influences the accessibility of the salt and the consistency of the product
Elucidating the interaction between chemesthesis and saltiness perception	Developing barriers for increased stability of double emulsions and finding new emulsifiers	Develop efficient techniques for application of salt on food surfaces, and to make fat-coated salt particles
The evolution of saltiness perception throughout consumption time	Developing techniques to investigate salt migration mechanisms at different length scales in systems with inhomogeneous salt distribution and coated salt particles	Ensure microbiological safety
Balance in flavor perception and focus on a holistic sensory perspective of a product during sodium reduction	Juiciness: investigate shelf-life stability and the relationship between serum release, microstructure, and saltiness	
Effect of additional modalities such as sound on saltiness	Investigate how microstructure influences brittleness, texture, and saltiness	
Further application of cross-modal principles to solid food matrices		
Competition between chemical components that binds to the same taste receptors as salt		
Development of new flavor-enhancers		
Interactions in multi-component dishes		

terms of saltiness perception (Crucean et al., 2019), but the replacement of salt with choline in some products could be met with resistance by consumers as salt is considered an essential ingredient in, for example, "traditional" French bread. Thus, all these aspects must be considered for each specific product when sodium salt is replaced by other ingredients (Inguglia et al., 2017; Shen et al., 2022).

3.5 | Strategies to reduce sodium content in different product categories

From the recent advances in the research reviewed in the literature, several methods and strategies can be utilized to reduce sodium content in foods (see Table 2). For each technique, the scientific approach and the method of execution have been compiled, together with their applications in potential food product categories. Some techniques show versatility in their application across several product categories. The techniques are not perfect, and challenges associated with each solution that require consideration have also been discussed. However, multiple approaches can be utilized concurrently within one product category, which have the potential to maximize the sodium reduction further than applying one technique in isolation.

4 | CONCLUSIONS AND FUTURE OUTLOOK

There is a strong demand for reduction of sodium in foods to improve human health. A large portion of sodium intake comes from food from producers or food services. There are many examples worldwide of sodium reduction using the stealth approach or by communication and legislation. However, these approaches are only feasible to a certain extent, as challenges regarding sensory perception, texture, microbiological safety, and processability become increasingly important at lower sodium content. This is because salt serves many different physicochemical functions in foods, including but not limited to decreasing water activity, altering the water binding capability of proteins, influencing the gelation of polysaccharides, and aggregation of proteins. Striking the right balance between addressing the above issues and understanding which boundaries can be pushed is key to successfully reducing sodium intake. Consequently, there is a strong need for technical solutions that are applicable on an industrial scale.

Several technical solutions (summarized in Table 2) that have the potential to reduce sodium and warrant further investigation have been identified in this review. All these solutions essentially boil down to the following principles:

1. Manipulating the taste system through pulsating salt concentration or multisensory combinations.
2. Controlling the time-dependent concentration of sodium that reaches the taste receptors through salt particle dissolution rate, increased serum release, double emulsions, and brittleness.
3. Substitution of sodium with other mineral salts and ingredients.

When implementing different solutions, it is important to consider the physical state (solid, fluid, semi-solid) of the food category of interest, as each matrix faces different challenges. It is also important to consider various processing solutions that can compensate for different challenges that occur with sodium reduction: the solution must be adopted to each specific product. The technical solutions can also be sorted in terms of interactions:

1. Chemical interactions
2. Physiological interactions in the mouth
3. Cognitive interactions in the brain

The theme of sodium reduction is a topic of on-going importance and interest, indicated not only by the number of published scientific articles but also by the prioritization by health boards and authorities worldwide. However, as discussed, sodium reduction also represents a significant challenge, and so continued research and innovation are imperative to identifying and implementing solutions that work at scale. The list of challenges to be addressed for future research and development in the areas of multisensory perception, structure and texture, and processing is provided in Table 3.

AUTHOR CONTRIBUTIONS

Niklas Lorén: Writing – review & editing; Conceptualization; Funding acquisition; Formal analysis. **Jun Niimi**: Writing — original draft; Writing – review & editing; Methodology; Investigation; Formal analysis. **Evelina Höglund**: Investigation; Methodology; Writing – review & editing; Writing — original draft; Formal analysis. **Rickard Albin**: Investigation; Writing — original draft; Writing – review & editing; Methodology; Formal analysis. **Elisabet Rytter**: Conceptualization; Funding acquisition; Writing — original draft; Visualization. **Karin Bjerre**: Investigation; Writing — original draft; Methodology; Writing – review & editing; Formal analysis. **Tim Nielsen**: Conceptualization; Funding acquisition; Project administration; Writing — original draft; Resources.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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