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PREFACE

The use of sodium chloride (most people know it as table salt) is everywhere in food processing. It does two main jobs: it makes food taste better and helps food last longer on shelves. For many years, these reasons have made salt a must-have in many foods. Still, in more recent times, this very same substance has landed at the center of many health debates.

There's been a rising awareness about non-communicable diseases across the world—like high blood pressure and heart issues. Big organizations, such as the World Health Organization, have increased their alerts about the dangers linked with eating too much sodium. Cutting back on daily sodium chloride isn't just suggested—it's seen as a major goal for countries everywhere. So naturally, the search for good options has become an important task for food scientists out there.

This book comes from both this sense of duty and pure curiosity. Inside, we've tried to collect and explain the latest research about lowering sodium chloride, with a special look at processed seafood. That covers smoked, marinated, canned, salted, and surimi-based products. In these foods, salt does more than just add flavor—it actually helps hold things together and keeps food safe.

But, lowering sodium chloride in these complicated foods isn't simple at all. Studies mention different answers: just using less, swapping some or all of it for salts like potassium, magnesium, or calcium chloride, and even putting in certain things (called masking agents) to cover up any odd tastes. Each method can be tricky and may work better (or worse) depending on which food it is, how customers feel, and what technology companies can handle.

We put this book together to share and explain the facts and options now available about sodium reduction in processed seafood. Our hope is for it to be useful—not just for scientists, but also food technologists and others in the industry, anyone trying to find the right mix between health, taste, and safety.

It's not only a stack of research. This work aims to be (as we see it) a much-needed back-and-forth—a conversation—between what the science says and what public health needs right now.

06/08/2025

Prof. Dr. Şükran Çaklı

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INTRODUCTION

Excessive sodium intake through diet represents a significant public health challenge both in Turkey and worldwide. Adults in Turkey consume about 15 grams of salt per day, which is three times the World Health Organization's recommended limit of 5 grams (Erdem et al., 2017). This heightened intake of sodium is closely linked to hypertension and an elevated risk of cardiovascular problems, including heart disease and stroke (World Health Organization, 2012). Health experts emphasize the need to reduce sodium consumption to prevent these outcomes, with a global aim to cut down on salt intake among populations by 30% by the year 2025 (Rybicka & Nunes, 2022). Reaching this goal requires comprehensive policy actions and increased public awareness of the health risks associated with salt.

Countries are adopting national and regional strategies to lower sodium intake through regulatory and educational initiatives. The primary dietary sources of sodium differ by region; however, processed foods and added salt remain the main contributors. In the United States, over 70% of sodium intake comes from commercially processed or restaurant-prepared foods (U.S. FDA, 2021), whereas in Turkey, bread and salt added during home cooking contribute to about 64% of daily salt intake. These differences call for sodium reduction strategies tailored to local eating habits. In regions where processed foods are the primary source of sodium, reformulating these products to contain less salt is a crucial strategy. In Turkey and similar settings, efforts focus on reducing salt in staple foods and encouraging reduced salt use in cooking (Erdem et al., 2017). Clear nutrition labeling is crucial across all settings to help consumers make lower-sodium choices. Many regions have introduced front-of-pack labels and warnings for high-salt products to increase awareness (Karppanen & Mervaala, 2006). Public education campaigns, such as national "Salt Awareness Week" programs, further inform consumers about the health risks of excess salt and methods to reduce intake (Rybicka & Nunes, 2022). Governments aim to create an environment supporting healthier, lower-sodium diets by combining policy action with consumer education.

Several nations have implemented successful sodium reduction programs, yielding notable health benefits. Finland's pioneering salt reduction campaign, initiated in the late 1970s, demonstrates the impact of comprehensive policy measures. Over three decades, Finland achieved a 30–35% reduction in average salt intake through public education, collaboration with food manufacturers, and mandatory "high salt" warning labels on foods (Karppanen & Mervaala, 2006). This sustained effort corresponded with a significant decrease in population blood pressure and an approximate 75–80% decline in stroke and coronary heart disease mortality (Karppanen & Mervaala, 2006). In Japan, something pretty similar happened too. Back in the 1960s, some parts of Japan had folks eating more than 15 to 18 grams of salt every day. That’s a lot—way above what’s safe. Because of this, Japan faced some of the highest stroke death rates in the whole world (Uechi et al., 2017). To tackle the problem, the Japanese government set up a big public education campaign. (It was all about getting people to eat less salt.)

Over the next ten years, folks really listened. Salt intake dropped. Stroke deaths went down too (Sugiyama et al., 2022). It's clear now—big public health steps can help people eat less salt and live healthier lives.

Lately, other countries—like the United Kingdom and the United States—have tried similar things to help people cut back on salt, with some pretty good results. The UK kicked off their salt reduction effort way back in the early 2000s. They didn't just do one thing; they tried many ideas at once. For example, they made goals for less sodium in different types of food, worked with food companies, put easy-to-understand "traffic light" labels on food packs, and started ads to warn people about eating too much salt (He et al., 2014).

Food companies in the UK (the big ones) slowly changed how they made popular foods—like bread, cereal, and snacks—so there was less salt in them. Over almost seven years, the UK got the average salt eaten each day down by 15%. That's a drop from about 9.5 grams to 8.1 grams per day. (Scientists checked this by testing entire days' worth of urine. Not the most fun job but very accurate!) (He et al., 2014).

Thanks to this country-wide work, both blood pressure and stroke deaths went down in the UK (He et al., 2014). This just shows that with the right public health actions, big changes in what people eat (especially salt) can really lead to healthier lives—not just in one place, but almost anywhere. Meanwhile, in the United States, where the average adult ingests approximately 3.4 grams of sodium daily (equivalent to about 8.5 grams of salt) (U.S. FDA, 2021), authorities have been advocating for voluntary reductions in sodium consumption. The U.S. Food and Drug Administration issued guidance in 2021 for food manufacturers and restaurants to gradually lower sodium levels in 163 categories of foods, aiming to help reduce average American sodium intake toward 2,300 mg (5.8 g salt) per day (U.S. FDA, 2021). While the U.S. program is ongoing, it reflects a commitment to similar strategies of product reformulation, improved labeling, and public awareness. These national initiatives underscore that concerted policy action can reduce sodium consumption at the population level.

Food manufacturers are employing various techniques to reduce sodium chloride in processed foods (including processed seafood) while maintaining safety and taste. Sodium chloride (common salt) serves multiple functions in food processing: enhancing flavor, preserving foods by inhibiting microbial growth, and influencing texture in products like bread and cured meats (Nurmilah et al., 2022). Consequently, reducing salt in processed foods can be challenging, and a combination of strategies is often employed. One approach involves gradual salt reduction over time, allowing consumer palates to adjust with minimal notice – a method that has been effective in the UK's reformulation program (He et al., 2014). Another key strategy is the use of salt substitutes or salt enhancers. Potassium chloride is commonly used to replace a portion of sodium chloride in foods, as it provides a salty taste without sodium; blends of potassium, magnesium, or calcium salts can achieve sodium reductions of 25–50% in certain products (Nurmilah et al., 2022). For instance, research on processed seafood products like smoked trout has shown that replacing a portion of NaCl with potassium chloride can significantly lower sodium content while maintaining product quality (Rybicka & Nunes, 2022). Flavor enhancers such as monosodium glutamate (MSG), yeast extracts, or umami-rich seasonings are also used to enhance savory taste in low-sodium recipes, helping to compensate for reduced salt (Nurmilah et al., 2022). Additionally, food technologists are exploring changes in food structure and salt distribution – for example, using smaller salt crystals or surface sprinkling – to maximize perceived saltiness so that less salt can be used overall (Nurmilah et al., 2022). In fermented or preserved products (including salted fish and other seafood), careful adjustments in formulation and processing can sometimes reduce salt requirements while still preventing spoilage (Rybicka & Nunes, 2022). Each of these methods requires careful testing to ensure that the final product remains safe and acceptable to consumers.

Reducing sodium chloride in processed foods (such as seafood) and across the diet is achievable through an integrated strategy. Governments are implementing policies – from mandatory labeling to voluntary reformulation targets – and promoting consumer awareness to encourage lower salt intake. Simultaneously, the food industry is utilizing new techniques for reducing sodium to produce healthier options. Examples from countries such as Finland, Japan, and the UK illustrate that ongoing salt reduction efforts can greatly enhance public health by reducing blood pressure and mitigating the risk of cardiovascular diseases (He et al., 2014; Karppanen & Mervaala, 2006). It is important to continue expanding and improving these initiatives while taking into consideration local dietary practices to effectively tackle the global issue of high sodium intake and its related health hazards (Nurmilah et al., 2022; World Health Organization, 2012).

1. REDUCING SALT IN FOODS

Researchers have spent a lot of time trying to lower sodium chloride in different foods. This is true for things like dairy, Meat, poultry, fish and even fermented foods. Much of this work puts a big focus on processed foods because they play such a huge part in how much sodium people eat every day (He et al., 2014; Rybicka & Nunes, 2022). This topic stays important, mostly because people worry more now about eating too much sodium. High salt intake has been linked to problems like high blood pressure, heart issues, and other health risks (Cappuccio & Capewell, 2015). In Table 1, you'll find a quick overview of key studies on cutting down sodium in many kinds of foods.

The main aim of this area of study is simple: find good ways to lower how much sodium chloride people eat, but keep food taste and texture the same so people still enjoy eating it. Newer studies show that using ingredients from nature—like herbs (think parsley or basil), spices, plant extracts, and even things left over from fruit and vegetable processing, for example peel or seeds turned into powder—can be real options. These items do two things: help cut the salt and also make foods taste and smell better (Nurmilah et al., 2022). Some even give extra good stuff (bioactive compounds) that might help health, too. Furthermore, alternative processing methods, such as non-thermal treatments, high-pressure processing (HPP), and cold plasma technology, have been explored to achieve sodium reduction without compromising food safety and quality (Rybicka & Nunes, 2022). However, these techniques require thorough evaluation of their economic viability, scalability in industrial settings, and overall consumer acceptance before widespread implementation (Sugiyama et al., 2022).

Among the numerous salt reduction strategies investigated, three main approaches are widely recognized for their efficacy. The most traditional and extensively researched method involves using salt substitutes, particularly potassium chloride (KCl), which replicates the functionality of sodium chloride but lacks its hypertensive effects (He et al., 2014). However, KCl imparts a metallic or bitter aftertaste, necessitating the addition of masking agents, such as amino acids, organic acids, or flavor-modulating compounds, to improve palatability (Nurmilah et al., 2022).

The second approach focuses on using flavor enhancers that do not inherently possess a salty taste but amplify the perception of saltiness when combined with sodium chloride. Monosodium glutamate (MSG), yeast extracts, nucleotides, and umami-rich compounds (such as hydrolyzed vegetable proteins) are commonly used in this regard, allowing for a significant reduction in added salt while maintaining the sensory characteristics expected by consumers (Karppanen & Mervaala, 2006).

A more recent and innovative strategy involves optimizing the physical structure of salt to increase its bioavailability and enhance saltiness perception with lower sodium content (Rybicka & Nunes, 2022). By altering crystal size, shape, and distribution, food scientists have developed microscopic salt particles and surface-applied salt technologies that maximize salt taste intensity while reducing overall sodium levels (Nurmilah et al., 2022). In particular, this technique has proven successful for items like snacks, processed meats, and seafood, where salt applied to the surface provides the desired flavor with considerably less sodium chloride.

Overall, reducing sodium in processed food remains a vital research field, necessitating a comprehensive strategy that combines advances in technology, innovations in ingredients, and consumer-centered approaches. As food scientists continue to enhance these methods, cooperation between academic institutions, the food industry, and regulatory authorities will be essential for effective application and for gaining wide consumer acceptance.

Table 1 Research on reducing salt in different foods

Methodology Summary	Method Applied	Results	Study	Citation
Investigated the combined effects of curcumin and sodium bicarbonate on beef protein properties for sodium reduction.	Conducted textural analysis and protein gelation studies on myofibrillar proteins.	Sodium bicarbonate enhanced protein stability, making sodium reduction in processed meats viable.	Effects of Curcumin and Sodium Bicarbonate on Beef Protein Structure	Chen, Y., et al., (2025)
Review assessing the impact of sodium reduction on food safety and quality.	Investigated sodium's role in microbial safety and evaluated alternative preservation methods.	Concluded that sodium reduction is possible without compromising food safety by using alternative preservatives.	Sodium Reduction and Food Safety	Doyle & Glass, (2010)
Analyzed the impact of partial sodium	Applied genomic sequencing and sensory evaluation to	Moderate sodium reduction was	Genomics and Formulation Optimization for Sodium	Ferrer-Bustins, N., (2024)

chloride replacement with potassium chloride on the microbial safety and texture of fermented sausages.	assess alternative salt formulations.	achieved while maintaining microbial safety and product texture.	Reduction in Fermented Sausages	
Assessed the feasibility of using seaweed extracts as a natural sodium substitute in processed meat.	Conducted sensory evaluation and chemical analysis of sodium-reduced meat formulations.	Successfully reduced sodium while maintaining flavor and increasing dietary fiber content.	Seaweeds as a Functional Ingredient for Sodium Reduction in Pork Nuggets	Goswami, M., et al., (2025)
Policy-based review on sodium intake reduction strategies.	Assessed government initiatives and proposed regulatory changes.	Recommended a 50% reduction in sodium in processed foods over 10 years through new labeling initiatives and	The Urgent Need to Reduce Sodium Consumption	Havas et al., (2007)

		reformulation.		
Systematic review and meta-analysis evaluating the effectiveness of behavior change interventions on salt consumption.	Analyzed multiple studies focusing on interventions such as education, counseling, and use of technology to promote reduced salt intake.	Found that behavior change interventions are effective at improving salt consumption practices and appear to reduce salt intake by more than 1 gram per day.	Behavior Change Interventions for Reducing Salt Intake	Saman Khalesi, et. al., (2022)
Study on how reducing sodium in foods affects overall nutritional intake.	Modeled sodium reduction scenarios and assessed their nutritional consequences.	Found that sodium reduction led to a significant decrease in daily intake, with minimal adverse effects on diet quality.	Nutritional Impact of Sodium Reduction	Hendriksen & Verkaik-Kloosterman, (2015)

Review of existing research on sodium reduction in fermented foods.	Direct NaCl reduction, NaCl substitution, structure modification, flavor enhancers, starter cultures, non-thermal processing.	Combination strategies are needed to maintain flavor while reducing sodium in fermented foods.	Insights into the flavor perception and enhancement of sodium-reduced fermented foods: A review	Hu et al., (2024)
Investigated the impact of sodium reduction strategies, including salt substitutes, on public health and food industry practices.	Analyzed sodium reduction policies, salt substitute adoption, and their effects on hypertension and cardiovascular risk.	Identified sodium reduction as a key factor in hypertension control, though widespread adoption of salt substitutes remains a challenge.	Dietary Sodium-and Potassium-Enriched Salt Substitutes—The Tipping Point?	Jones, D. W., et al., (2025)
Experimental consumer study on sodium reduction in snacks.	Blind and informed consumer testing of salt-reduced potato chips.	30% sodium reduction possible without significant loss in palatability.	Consumer perception of salt-reduced potato chips: Sensory strategies, effect of	Kongstad & Giacalone, (2020)

			labeling and individual health orientation	
Investigated how vegetable extracts could enhance saltiness perception in sodium-reduced emulsions.	Performed sensory analysis and molecular stability assessments of sodium-reduced emulsions.	Vegetable extracts allowed a 30% reduction in sodium without affecting taste perception.	Stabilization and Sensorial Characterization of Sodium-Reduced Emulsions	Lee, J., Byeon, Y. M., & Choi, M. J. (2025)
Experimental study using taste contrast and sodium retention analysis.	Use of gum arabic to enhance salt perception and reduce sodium in food.	Up to 30% salt reduction achieved in yogurt and mayonnaise without loss of saltiness.	Salt reduction in liquid/semi-solid foods based on the mucopenetration ability of gum arabic	Li et al., (2019)
Evaluation of sodium reduction efforts in community meal programs over three years.	Food service guidelines, procurement practices, food preparation modifications.	Sustained sodium reductions of up to 40% achieved in community meal programs.	Reducing Sodium Intake in Community Meals Programs: Evaluation of the Sodium Reduction in	Long et al., (2021)

			Communities Program	
Evaluation of sodium reduction in school meal programs over five years.	Food service guidelines, procurement modifications, environmental strategies.	14% sustained sodium reduction achieved over five years.	Reducing Sodium Content of Foods Served in Arkansasâ€™s Largest School District	Long et al., (2022)
Evaluation of novel strategies for reducing sodium in different food products.	Studied how sodium interacts with food matrices and explored new reduction techniques.	Suggested innovations in ingredient interactions to optimize sodium reduction while maintaining product quality.	Technical Innovations for Sodium Reduction	Lorén et al., (2023)
Analysis of sodium content trends in packaged foods from 2009 to 2018.	Monitoring sodium reduction initiatives in packaged foods.	Sodium reduction slowed after 2014 due to lack of federal regulations.	U.S. Food Industry Progress Towards Salt Reduction Slowed Without	Moran et al., (2020)

			Sodium Targets	
Narrative systematic review on the effectiveness of technology-supported interventions for reducing salt intake.	Reviewed studies utilizing digital tools and applications to promote behavior change in salt consumption.	Concluded that technology-supported behavior change interventions improved sodium intake behavior and/or reduced sodium intake.	Technology-Supported Behavior Change Interventions	Yan, Y. Y., et al., (2024)
Traditional review methodology with practical and methodological screening.	Salt replacement, food reformulation, size and structural modifications, alternative processing, crossmodal odor interaction, gradual salt reduction.	Multiple strategies can effectively reduce sodium while maintaining product quality.	Strategies to Reduce Salt Content and Its Effect on Food Characteristics and Acceptance: A Review	Nurmilah et al., (2022)

Nutrient analysis before and after sodium reduction initiatives.	Lower sodium product replacement, ingredient reduction, high sodium ingredient removal.	Average sodium reduction of 314 mg per food item; replacement strategy was most effective.	Effective Strategies to Reduce Sodium in the Local Food Environment at Worksites and Congregate Sites	Ullevig et al., (2019)
Experimental study on modifying salt particle size for enhanced perception.	Spray drying and electrohydrodynamic atomized drying for salt modification.	58-65% sodium reduction possible while maintaining perceived saltiness.	Size-dependent enhancement in salt perception: Spraying approaches to reduce sodium content in foods	Vinitha et al., (2021)
Investigated how replacing sugar with oligosaccharides and d-allulose affects sodium perception in bread.	Conducted baking trials, sensory evaluations, and structural analysis of sodium-reduced bread.	Achieved significant sodium reduction without compromising taste or texture.	Sugar Reduction and Sodium Control in Bread Using Alternative Sweeteners	Xiao, Z., et al., (2024)

Examined the ability of chickpea protein-based hydrogels to regulate sodium release in food products.	Used microstructure analysis and molecular dynamics simulations to assess sodium retention and release properties.	Demonstrated controlled sodium release, improving taste perception while reducing total sodium content.	Characterization of a Novel Chickpea Protein-Pullulan Hydrogel for Sodium Reduction	Zhang, K., et al., (2025)

2. REDUCING SALT IN SEAFOODS

Processed seafood products, particularly anchovies, smoked fish, and marinated seafood, are among the most sodium-dense food items due to their reliance on salt for preservation and sensory attributes (Rybicka & Nunes, 2022). Given the rising health concerns associated with excessive sodium intake, a growing body of research has been dedicated to reducing salt levels in seafood while maintaining product quality and consumer acceptability.

Table 2 provides a summary of various methodologies employed in recent studies to achieve sodium reduction in seafood processing.

Table 2 Research on reducing salt in different Seafoods

Methodology Summary	**Method Applied**	**Results**	**Citation**
The study aimed to develop smoked trout with reduced sodium chloride (NaCl) content without compromising quality and safety. It involved a literature review of current NaCl reduction strategies, benefit-risk assessments of NaCl replacements, and experimental studies on smoked trout.	Experimental reduction of NaCl in smoked trout, assessing quality and safety parameters.	The study successfully optimized the development process for smoked trout with reduced NaCl content, maintaining both quality and safety.	Rybicka, I., et al., (2022)
Investigates bio-preservatives as alternatives to reduce salt and chemical use in seafood preservation.	Experimental study analyzing natural bio-preservatives on different seafood products.	Bio-preservatives effectively reduce salt use and extend shelf life.	Hassan, S., & Hayat, B. U. (2024)

Examines salt reduction in shellfish processing.	Utilizes freshwater rinsing to remove excess salt from mussels.	Freshwater rinsing significantly reduces salt content while maintaining protein integrity.	Adler, I., Kotta, J., & Tuvikene, R. (2024)
Evaluates ultrasound-assisted brining to reduce salt usage in shrimp processing.	Applies high-intensity ultrasound during brining.	Maintains water-holding capacity while reducing salt penetration.	Bernardo, Y. A., & Monteiro, M. L. G. (2024)
Investigates alternative seafood preservation methods with reduced salt.	Uses high-pressure processing (HPP) on fermented clam jeotgal.	HPP significantly reduces microbial activity, lowering salt requirements.	Jeon, E. B., Jeong, H. S., & Park, S. Y. (2024)
Evaluates enzyme-assisted processing to reduce salt use in seafood hydrolysis.	Uses alkaline proteases from rose snapper to improve processing efficiency.	Enzymatic hydrolysis reduces salt dependency while maintaining protein integrity.	Rios-Herrera, G. D., et al., (2024)
Examines microplastic contamination in seafood and its role in salt absorption.	Analyzes salt diffusion rates in seafood exposed to microplastics.	Microplastics increase salt retention in processed seafood.	Zajác, P., Čapla, J., & Čurlej, J. (2025)

Evaluates innovative food packaging for salt reduction in seafood.	Uses nanoparticles and natural preservatives in packaging.	Green nanoparticle packaging extends seafood shelf life without added salt.	Rahman, S. M. E., Wang, J., & Wang, H. (2024)
Reviews traditional seafood preservation methods and modern packaging innovations.	Compares traditional salted seafood with new low-sodium packaging solutions.	Modern packaging allows for salt reduction without compromising preservation.	Seifzadeh, M. (2024)
Examines the effects of drying techniques on salt retention in seafood.	Uses comparative studies of dried and fresh seafood salt content.	Drying reduces the need for added salt while preserving quality.	Aman Hassan, (2024)
Analysis of industry trends in reducing salt in seafood.	Case study and industrial survey.	Highlights challenges in further reducing salt in seafood without compromising texture and safety.	Pedro, S., & Nunes, M. L. (2019)
Risk-benefit analysis of replacing NaCl with alternative salts.	Experimental study using sensory and microbiological analysis.	Substitutes such as KCl maintain sensory quality but require further	Rybicka, I., & Nunes, M. L. (2022)

		optimization to ensure safety.	
Overview of mild processing techniques to reduce salt.	Literature review with technological insights.	Methods such as high-pressure processing (HPP) improve salt reduction efficacy.	Abel, N., Rotabakk, B. T., & Lerfall, J. (2022)
Systematic review of microbiological, physicochemical, and sensory effects of sodium replacement.	Meta-analysis of previous studies.	Replacing sodium with alternative salts affects microbial stability and sensory attributes.	Gomes, M. S. A., Kato, L. S., & de Carvalho, A. P. A. (2021)
Study on salt reduction in whole meat and seafood products.	Analysis of sodium chloride absorption in cured products.	Reduced absorption achieved by modifying processing methods.	Domínguez, R., & Pateiro, M. (2017)
Examines how salt influences lipid oxidation in seafood.	Experimental study on lipid oxidation rates in different salt concentrations.	Higher salt concentrations increase oxidation, affecting flavor and quality.	Mariutti, L. R. B., & Bragagnolo, N. (2017)

Overview of sodium reduction strategies in salted seafood and meat products.	Nutritional analysis and processing methods review.	Sodium alternatives like calcium chloride and potassium chloride show promise but affect taste and texture.	Vidal, V. A. S., Paglarini, C. S., & Lorenzo, J. M. (2023)
Investigates how high hydrostatic pressure (HHP) processing reduces salt levels while preserving texture and microbiological stability.	Experimental study with varying pressure levels and salt concentrations.	HHP effectively reduces the need for added salt while maintaining product safety and sensory attributes.	Zhang, X., & Wu, T. (2022)
Experimental study assessing the effect of NaCl reduction on physicochemical, microbiological, and sensory properties.	Partial replacement of NaCl with KCl or oleoresins microcapsules.	NaCl reduction affected texture and taste but was mitigated over 5 weeks; replacement with KCl improved potassium intake.	Estévez, A., et al., (2021)
Experimental evaluation of sodium reduction using microbiological,	Partial replacement of NaCl with Saltwell®, a natural mix of NaCl and KCl.	22% sodium reduction was achieved without affecting microbial activity; minor	Nielsen et al., (2020)

sensory, and chemical analyses.		sensory differences observed.	
Experimental study assessing taste and nutritional composition after replacing NaCl with KCl and yeast extracts.	50% NaCl replaced with KCl; yeast extract used to mask bitterness.	Despite 50% NaCl reduction, umami taste improved due to increased amino acids.	Sen Yılmaz, (2023)
Analysis of marinated anchovy quality with partial NaCl replacement using physical and sensory tests.	50% NaCl replaced with KCl.	Maintained physical and sensory qualities similar to 100% NaCl samples.	Erol et al., (2021)
Comprehensive review assessing the benefits and risks of NaCl alternatives in seafood.	Literature review and experimental tests on smoked trout.	Optimization of NaCl replacement without compromising safety and quality.	Rybicka & Nunes, (2022)
Experimental study evaluating different NaCl replacements and their effects on physicochemical	Various NaCl replacements (KCl, CaCl2, yeast extract, lysine, taurine) tested in	30% NaCl replacement with KCl had minimal sensory impact; yeast extract improved taste.	Wang et al., (2021)

and sensory properties.	different combinations.		
Comparative analysis of NaCl reduction in Matjes nordische Art and cold-smoked salmon.	Partial NaCl replacement with KCl, potassium lactate, and commercial salt substitutes.	Significant NaCl reduction achieved without microbial or sensory deterioration.	Giese et al., (2019)
A consumer-based study applying the Just Noticeable Difference (JND) method for gradual NaCl reduction.	Stepwise NaCl reduction in chorizo and sausages to find unnoticed reduction levels.	Achieved up to 22% salt reduction without perceptible differences in taste.	Cubero-Castillo et al., (2019)
Review summarizing strategies for salt reduction using multisensory cues.	Gustatory, olfactory, auditory, visual, and tactile enhancements to reduce NaCl intake.	Multisensory approaches help maintain flavor perception while reducing NaCl.	Liu et al., (2024)
Systematic review of salt intake and reduction strategies in South Asian countries.	Analysis of dietary sodium intake data and public health interventions.	High salt intake persists; policy-based strategies are required for reduction.	Ghimire et al., (2021)

Sodium chloride (NaCl) has been important in the processing of seafood for a very long time. It makes the flavor better. It helps keep seafood safe. It also keeps the texture right and holds in moisture (Nurmilah et al., 2022). In some other foods, sodium mostly just boosts taste, but that's not all it does here. Salt in seafood matters a lot more. It keeps seafood safe because seafood spoils fast from bacteria (Jeon et al., 2024).

So, if you want to lower sodium in processed seafood, it's not enough just to switch salt with something else. You need several smart steps (and careful planning) to keep the food safe. You must also keep the taste good, the texture right, and the shelf life long (Hassan & Hayat, 2024).

Salt does many important things for seafood. It pulls out water from the product—a process called osmotic dehydration. By doing this, it stops bad germs from growing. It brings down water activity and that makes the seafood last longer (Gomes et al., 2021).

This feature, in particular, is very important. It matters a lot for things like salted anchovies, smoked salmon, and marinated fish. These are called fermented, cured, or dried products. If you cut too much salt, these items can become unsafe or spoil much quicker.

Keeping the balance takes real care. That's why, when lowering salt, a well-thought-out plan is needed (sometimes even extra steps) to preserve both the safety and quality of seafood. Furthermore, salt increases protein solubility and enhances water-binding capacity, which helps in preventing significant moisture loss in both frozen and processed seafood (Rahman et al., 2024).

In mechanically processed products like fish sausages and surimi-based items, sodium chloride aids in the gelation of myofibrillar proteins, influencing texture and firmness (Vidal et al., 2023).

Given these essential functions, any attempt to reduce sodium in seafood must ensure that functional properties, microbial safety, and sensory acceptability are not compromised.

A common approach to sodium reduction involves partially substituting NaCl with alternative salts, primarily potassium chloride (KCl) (Rybicka & Nunes, 2022). Potassium chloride can effectively mimic the functional properties of sodium chloride, particularly in maintaining water-holding capacity and controlling microbial activity. However, research indicates that replacing more than 50% of NaCl with KCl results in a noticeable bitter and metallic aftertaste, diminishing consumer acceptability (Şen Yılmaz, 2023).

To address these sensory challenges, various masking agents and flavor enhancers have been investigated. Yeast extracts (Levex Simplo and Levex Terra), monosodium glutamate (MSG), nucleotides (inosine monophosphate and guanosine monophosphate), and umami-rich compounds have been incorporated to enhance the perceived saltiness of seafood while counteracting the undesirable taste of KCl (Ando, 2020). Moreover, the use of magnesium salts, calcium chloride ($CaCl_2$), and sodium lactate in combination with KCl has shown potential in preserving flavor without excessive sodium content (Wang et al., 2021). However, the efficacy of these substitutes varies by product type, processing method, and consumer preference, necessitating further refinement.

3. SALT CONCENTRATION REDUCTION TECHNIQUES

Processed seafood makers are working together now, combining food tech, sensory testing, and public health to bring down salt levels. The usual way of using salt — for keeping food safe, making it taste good, and stopping germs — gets a lot more attention now because too much salt is bad for health. That’s why new methods are coming up to keep seafood safe and tasting good, but with less sodium inside.

3.1. High-Pressure Processing (HPP)

High-Pressure Processing (HPP) is a pretty new, non-heat food saving method. It kills off germs and things that spoil food, while keeping food’s taste and quality. Unlike using heat, which can mess up both the texture and vitamins, HPP lets seafood stay tasty. It also means you don’t need as much salt to keep seafood safe. This works especially well for cured or fermented seafood. Think of salted mackerel or pickled anchovies. With HPP, the sodium in these foods can be much lower, but the shelf life and safety don’t go down. So, HPP gives another way to salt seafood, not just the usual ways (Jeon et al., 2024).

3.2. Ultrasound-Assisted Brining

Using powerful ultrasound sound waves in brining changes the game. It helps salt get inside the seafood better and faster. These sound waves make cells open up, and break the tiny parts, so that salt can spread evenly. This makes it possible to use weaker brine—less salt—but still keep the food safe. In shrimp factories, for example, ultrasound-brining means shrimps keep more water, and you don't have to wait as long for the salt to move in. These things are super important if you want to use this in real seafood factories and not just in a lab (Bernardo & Monteiro, 2024).

3.3. Freshwater Rinsing and Low-Sodium Marination

For shellfish like mussels and clams, washing them with fresh water after soaking in brine works well. This simple rinse gets rid of extra salt on the outside, so the final seafood has less sodium inside. Washing like this won't hurt the shape or the protein in the shellfish either, so it's a safe step to add (Adler et al., 2024). Also, marinating seafood with things like lemon juice, vinegar, or even other acids, plus natural stuff that helps keep food safe, can really cut down on salt use. If you do it right, you still get good taste and kill off germs, which is the main goal (Hassan & Hayat, 2024).

3.4. Modified Salt Crystal Structures

There is another trick—changing what salt looks like and how it's given out in food. If you make salt crystals smaller, or put them in just the right spots, they melt faster on the tongue, and you taste more salt even when there's less of it. Mixing tiny salt pieces, putting salt just on top, or spreading it unevenly in food like smoked trout and fish fillets, makes people think it's salty, though you actually use less sodium. Studies even show you can cut sodium by around 30% this way, with almost no change in taste (Wang et al., 2021; Rybicka & Nunes, 2022).

3.5. Alternative Packaging Technologies

New packaging can help seafood keep fresh, even with less salt. Some companies are making special films from plants or biopolymers, mixed with safe, tiny particles that kill germs. These films let companies lower sodium because they don't have to rely just on salt to keep fish and seafood safe (Rahman et al., 2024). This is handy for smoked or marinated foods that need less traditional salt protection but still must stay good longer.

4. REGULATORY CONSIDERATIONS AND CONSUMER ACCEPTANCE

Even though all these new ways are out there to cut sodium, there are still a few big hurdles—rules and what people will accept.

4.1. Regulatory Guidelines

Food safety regulators, like the European Food Safety Authority (EFSA) and the US Food and Drug Administration (FDA), tell companies to lower sodium in processed food (U.S. FDA, 2021). Any cuts in salt must still meet strict food safety laws, especially for ready-to-eat seafood. Salt is super important for stopping germs from growing, so you can't skip it just anywhere or anyhow.

4.2. Health Concerns and Potassium Intake

One common way to lower sodium is by swapping in potassium chloride instead. This works, but if people eat too much potassium, it can actually be dangerous—mainly for anyone with kidney problems or heart issues, or some rare health cases (FSAI, 2023). Now, more focus is on staying away from big potassium increases, using enzyme tricks and new supplement ideas.

4.3. Consumer Acceptance and Sensory Perception

What people think about taste really matters for these new lower-salt seafood foods. Step-by-step lowering of salt, not all at once, is shown to work better because people get used to the change (Cubero-Castillo et al., 2019). Plus, adding in umami-rich stuff like glutamates, fermented bits, or special enzymes can boost taste, even when salt is much less (Vidal et al., 2023). That helps keep people happy with how seafood tastes, so they buy it again.

5. FUTURE DIRECTIONS IN SODIUM REDUCTION FOR SEAFOOD PROCESSING

As seafood keeps changing, things like biotech, computer models, and sensory science are making new ways to cut sodium.

5.1. Peptide-Based Salt Enhancers

Recent studies show that small protein bits, called peptides, taken from seafood, can act like salt on the tongue. They trick your mouth, making you feel food's salty even with less salt overall (Zhang et al., 2024). This means you can use something natural instead of fake flavors or lots of sodium.

5.2. Fermentation-Based Salt Reduction

Careful fermentation, using good-for-you germs and enzymes, is catching attention. It makes food taste more umami, which helps in products like fish sauce. The microbes make extra flavorings, so you don't need as much added salt anymore (Nagai et al., 2020).

5.3. Artificial Intelligence in Food Reformulation

AI is now pretty important in planning out foods. Computer models can test out different amounts and types of salt—and even guess how people will like the new product—before companies ever make it for real (Ma et al., 2024). This cuts down on guessing and saves time, too, which is a huge win for seafood makers.

Reducing sodium in processed seafood remains a complex yet essential challenge that demands a multifaceted approach incorporating salt substitutes, advanced processing techniques, and consumer-focused formulation strategies. As regulatory bodies push for lower sodium levels in processed foods, further research is needed to develop safe, cost-effective, and consumer-friendly solutions that balance public health priorities with industry feasibility (Table 3).

Table 3 Studies on different salt reduction strategies and bitter taste removal in foods and seafood

Title of the Study	**Materials and Methods**	**Results**	**Reference**
Salt Reduction Strategies and Enhanced Saltiness Perception in Food	Reviewed current salt reduction strategies, including the use of flavor peptides and green technologies, and analyzed their effects on saltiness perception and bitterness masking.	Found that flavor peptides combined with new green technologies can effectively reduce salt content without compromising taste, and can mask bitterness associated with salt reduction.	Lan & Chen, (2024)
Umami and salt reduction	Used umami compounds like monosodium glutamate (MSG) to evaluate their effect	MSG improved palatability in salt-reduced foods; its effect on taste perception varied with	Ando, (2020)

	on salt reduction and palatability in foods across different regions.	concentration and food type.	
Comparing the taste-modifying properties of nanocellulose and carboxymethyl cellulose	Compared the bitterness reduction ability of nanocellulose (NFC) and carboxymethyl cellulose (CMC) through sensory analysis using trained panelists.	CMC was more effective than NFC in reducing bitterness due to its interaction with bitter compounds, while NFC had an astringent effect.	Manninen et al., (2021)
Effect of Piperine on Saltiness Perception	Determined detection threshold of piperine and its impact on saltiness perception in model solutions and soups using sensory evaluation methods.	Piperine increased saltiness perception but also enhanced bitterness and suppressed sweetness, limiting its effectiveness as a masking agent.	Moss et al., (2023)
Role of taste receptors in salty taste perception of minerals and amino acids and developments in salt	Reviewed research on taste receptor involvement in salty taste perception and how minerals/amino acids influence	Amino acids and minerals play a role in salt perception and can help mitigate the sensory downsides of salt reduction.	Sood et al., (2024)

reduction strategies: A review	sodium reduction strategies.		
Dynamic aspects of salt reduction in tomato sauce by use of flavor enhancers and a bitter blocker	Sensory analysis using trained panels and consumers to evaluate flavor enhancers and bitter blockers in tomato sauce with 50% salt reduction.	Lysine as a bitter blocker was ineffective; flavor enhancers improved initial taste but weakened over time; bitterness was not dominant in final samples.	Tavares Filho et al., (2020)
Sodium, but not potassium, blocks bitterness in simple model chicken broths	Tested sodium and potassium salts in model chicken broths with added bitterness from L-tryptophan; conducted sensory evaluations with human participants.	NaCl significantly suppressed bitterness, while KCl did not; sodium plays a key role in masking bitterness in foods with salt reduction.	Wise et al., (2019)
Sodium Chloride Suppresses the Bitterness of Protein Hydrolysates by Decreasing Hydrophobic Interactions	Used electronic tongue analysis to study the effect of NaCl on bitterness reduction in protein hydrolysates, along with physicochemical	NaCl reduced bitterness in protein hydrolysates by altering hydrophobic interactions, suggesting its effectiveness in masking bitter tastes.	Xu et al., (2019)

	property assessments.		
Bitter-blockers as a taste masking strategy: A systematic review towards their utility in pharmaceuticals	Review of various bitter-masking agents including caffeic acid and its salts, applied to food and pharmaceuticals. Sensory evaluation and chemical assays were analyzed.	Caffeic acid derivatives were found to be effective in masking bitterness in salt-reduced foods.	Andrews, D., et al., (2021).
Effect of Bitterness Blockers in Partial and Complete Replacement of Sodium Chloride with Potassium Chloride	Tested different bitterness-masking agents in meat products using sensory evaluation, focusing on partial and full KCl substitution.	Bitterness blockers significantly improved acceptability, reducing metallic and bitter notes, making KCl substitution more viable.	Arriaga, A. G. O. (2016)
Strategies for the Reduction of Salt in Food Products	Analyzed different approaches, including encapsulated salt and bitterness blockers, to	Microencapsulation of KCl helped in reducing bitterness, while glycosides were effective bitterness	dos Santos, M., Triviño, A. P. R., & Barros, J. C. (2023)

	improve low-sodium food acceptance.	blockers in sodium-reduced products.	
Methods for Removing Bitterness in Functional Foods and Nutraceuticals	Systematic analysis of various bitter-masking techniques including sweeteners, bitter blockers, and umami-based agents.	Umami substances such as monosodium glutamate (MSG) were identified as effective in masking bitterness in reduced-sodium foods.	Goldberg, E., Grant, J., & Aliani, M. (2017).
Hollow Salt for Sodium Reduction in Foods: Mechanisms, Influence Factors, Applications, and Challenges	Investigated the potential of hollow salt technology combined with bitter taste masking agents in sodium-reduced food production.	Hollow salt technology reduced bitterness from sodium-replacement agents like KCl, improving the overall taste perception of sodium-reduced foods.	He, M., & Tan, M. (2024)
κ-Carrageenan Masking Bitterness Perception in Surimi Gels Containing Potassium Chloride-Based Salt Substitutes	Analyzed the ability of κ-carrageenan to mask the bitterness of potassium chloride in surimi gels, using sensory evaluation and oral processing analysis.	κ-Carrageenan effectively masked the bitterness perception while maintaining saltiness, offering a promising alternative for sodium reduction.	He, N., et al., (2024)

Taste Characteristics of Salty Peptides from Porphyra haitanensis and the Synergistic Saltiness Enhancement with CaCl2	Studied the interaction between salty peptides derived from seaweed and calcium chloride (CaCl2) as a sodium-reduction strategy.	The peptides enhanced saltiness perception while masking the bitter taste of CaCl2, making it a viable alternative in salt reduction.	Huang, X., et al., (2024)
Natural biopolymer masks the bitterness of potassium chloride to achieve a highly efficient salt reduction for future foods	Study used natural biopolymer-based masking agents to reduce bitterness of potassium chloride (KCl) as a salt substitute. Sensory evaluation and chemical analysis were conducted.	The study showed that biopolymer masking significantly improved the sensory perception of KCl, making it a viable salt replacer.	Lu, W et al., (2022).
Utilization of Yeast Extract as a Flavor Enhancer and Masking Agent in Sodium-Reduced Marinated Shrimp	Investigated the impact of yeast extract (Torula) as a natural flavor enhancer and bitter taste masking agent in sodium-reduced shrimp formulations. Sensory evaluation	Yeast extract successfully masked the bitterness from potassium chloride (KCl) replacement, enhancing umami taste while maintaining consumer acceptability.	Ege University Scientific Research Projects Coordination Unit. Project Number: FGA-2019-20614 and

	and chemical analysis were conducted.		Şen Yılmaz, E. B. (2023)
Reduction of Sodium Chloride: A Review	Reviewed natural and synthetic bitterness blockers in sodium-reduced foods, including their mechanisms and applications.	Reported success of sweetness-enhancing compounds (glycosides, thaumatin) in masking bitterness associated with salt reduction.	Shen, D., Song, H., Zou, T., & Raza, A. (2022)
Especially in seafood			
Umami and salt reduction	Study on the impact of monosodium L-glutamate (MSG) on taste perception and salt reduction across different age groups in Japan.	MSG improved palatability of reduced salt foods, with stronger effects observed in lower salt concentrations.	Ando, (2020)
Bitter-blockers as a taste masking strategy: a systematic	Systematic review of bitter-blocking agents used in pharmaceuticals, assessing their mechanisms, safety, and	Sodium acetate, sodium gluconate, and adenosine 5'-monophosphate were identified as promising	Andrews et al., (2021)

review towards their utility in pharmaceuticals	effectiveness in masking bitterness.	bitter-blocking agents with good usability and safety profiles.	
Effect of Monosodium Glutamate on Salt and Sugar Content Reduction in Cooked Foods for the Sensory Characteristics and Consumer Acceptability	Sensory and hedonic evaluation of Korean foods with different salt levels, with and without MSG, assessed for bitterness suppression and taste enhancement.	MSG addition suppressed bitterness while enhancing umami and saltiness, allowing for a 23% sodium reduction while maintaining consumer acceptability.	Chung et al., (2022)
Dynamic aspects of salt reduction in tomato sauce by use of flavor enhancers and a bitter blocker	Sensory profile of tomato sauce formulated with flavor enhancers and a bitter blocker was studied using temporal dominance of sensations (TDS) and time-intensity analysis (TI).	Flavor enhancers initially improved sensory acceptance, but their masking effect weakened over time. Lysine was the least effective bitter blocker.	Rogério Tavares Filho et al., (2020)
Using taste-induced saltiness enhancement for reducing sodium in	Cheddar cheese with 75% NaCl replaced by KCl, evaluated with hydrolyzed vegetable protein (HVP) and adenosine-5â€²-	Hydrolyzed vegetable protein and AMP effectively masked KCl's bitterness, improving flavor and	Khetra et al., (2019)

Cheddar cheese: Effect on physico-chemical and sensorial attributes	monophosphate (AMP) as bitter blockers.	sensory acceptability in reduced sodium cheese.	
Effect of Piperine on Saltiness Perception	Piperineâ€™s effect on saltiness perception was tested using sensory evaluation and a trained panel. Its impact on bitterness and salt perception was analyzed.	Piperine increased saltiness perception but also enhanced bitterness, indicating potential cross-modal interactions in sensory perception.	Moss et al., (2023)
Reduced-salt shrimp sauces from Alaskan pink shrimp and nonglutinous rice cultivar Tsuyahime koji: Preparation and characterization	Low-sodium shrimp sauce was developed using koji fermentation to balance umami and bitterness. Sensory analysis and chemical composition were examined.	Reduced-sodium shrimp sauces had high umami intensity with low bitterness and were acceptable in sensory evaluations.	Nagai et al., (2020)
Sodium, but not potassium, blocks bitterness in	Model chicken broths with sodium chloride (NaCl) or potassium chloride (KCl) were tested for their ability to	Only NaCl suppressed bitterness in chicken broths; KCl was ineffective in masking bitterness.	Wise et al., (2019)

simple model chicken broths	suppress bitterness in the presence of L-tryptophan.		
Sodium Chloride Suppresses the Bitterness of Protein Hydrolysates by Decreasing Hydrophobic Interactions.	Study on the effect of NaCl in suppressing bitterness of protein hydrolysates using electronic tongue measurements and physicochemical analysis.	NaCl significantly suppressed bitterness by reducing surface hydrophobicity of peptides, making it an effective and low-cost masking agent.	Xu et al., (2019)
Partial replacement of sodium in fish products using magnesium salts	Experimental study on the use of magnesium-based salts to replace NaCl in processed seafood.	Magnesium salts were effective in reducing sodium but required flavor enhancers to counteract bitter and metallic aftertaste.	Barat, J. M., et al., (2013)
Influence of Sodium Chloride on Human Bitter Taste Receptor Activity	Explored the inhibitory effects of sodium salts on the human bitter taste receptor TAS2R16 using in vitro assays with salicin as the bitter compound. Dose-dependent studies were performed to determine the effectiveness of	Sodium chloride demonstrated a considerable and dose-dependent reduction in TAS2R16 receptor activity, indicating its potential role in masking bitterness in food products.	Kumar & Behrens, (2024)

	sodium chloride in bitterness suppression.		
Physical approaches to masking bitter taste: lessons from food and pharmaceuticals	Quinine bitterness in fish oil-in-water emulsions evaluated.	Some physical techniques successfully masked bitterness.	Coupland & Hayes (2014)
Reducing salt: A challenge for the meat industry	Combination of masking agents and flavor enhancers tested.	Effective in reducing bitter taste of KCl while maintaining sodium-like taste.	Desmond, E. (2006)
Salt microspheres and potassium chloride usage for sodium reduction: Case study with sushi	Application of salt microsphere technology and KCl in sushi seasoning.	Salt microspheres improved salt perception while reducing overall sodium content without increasing bitterness.	Đorđević, Đ., & Buchtová, H. (2018)
Sensory impact of sodium reduction strategies and the potential of	Comparison of various salt reduction strategies in processed seafood.	50% salt reduction was achieved with KCl and taste enhancers without	Dunteman, A. N. (2023)

flavor enhancement in nutritionally improved foods		significant sensory deterioration.	
Sensory issues in reducing salt in food products	Saltâ€™s impact on water-holding capacity in meat and fish.	Masking agents used in pharmaceuticals also apply to seafood.	Kilcast & Den Ridder (2007)
Reduction in Flavor-Intense Components in Fish Protein Hydrolysates Using Membrane Filtration	Applied membrane filtration techniques to fish protein hydrolysates to reduce bitter-tasting peptides. The treated hydrolysates were then incorporated into seafood products, and sensory evaluations were conducted to assess bitterness and overall flavor.	Membrane filtration effectively reduced the concentration of bitter peptides, leading to improved flavor profiles in seafood products without the need for additional salt.	Steinsholm, et. al., (2021)
Salt taste receptors and associated salty/salt taste-enhancing peptides: A comprehensive review	Peptides derived from fish skin collagen evaluated for salt taste enhancement.	Certain peptides were effective in masking bitterness.	Le et al. (2022)

Natural biopolymer masks the bitterness of potassium chloride to achieve a highly efficient salt reduction for future foods	Evaluation of natural biopolymer coatings as taste-masking agents for KCl in seafood processing.	The biopolymer significantly masked bitterness while maintaining the saltiness of the product.	Lu, W., et al., (2022)
Effects of umami substances as taste enhancers on salt reduction in meat products: A review	Study on the role of umami compounds like monosodium glutamate (MSG) and inosinate in counteracting bitterness in salt-reduced seafood.	Umami enhancers significantly improved consumer acceptance of salt-reduced seafood.	Ma, F., et al., (2024)
Reducing salt levels in seafood products	Different salt substitutes and their effects on taste.	Salt imparts a bitter flavor; no specific masking agents discussed.	Pedro, S., & Nunes, M. L. (2019)
Salt reduction in seafood–A review	A comprehensive review of various salt reduction methods in seafood processing, including the use of flavor enhancers	The study highlights yeast extract and umami compounds as effective masking agents that reduce	Rybicka, I., Oliveira, H., & Marques, A. (2022)

	and bitterness-masking agents.	bitterness without compromising taste.	
Effect of salt content reduction on food processing technology	Experimental study using potassium chloride (KCl) and other flavoring agents to reduce salt content in fish products.	KCl effectively reduced sodium content, but its bitterness required additional masking agents such as glycine and ribonucleotides.	Rysová, J., & Šmídová, Z. (2021)
Strategies for salt reduction in foods	Review of patents and research studies related to salt reduction in processed seafood and fish.	Masking agents, including phosphates and peptides, showed significant promise in taste improvement.	Toldrá, F., & Barat, J. M. (2012)
Low-sodium meat products: retaining salty taste for sweet health	Flavour enhancers and masking agents used to improve taste in low-sodium meat and fish products.	Reduction of metallic and bitter flavors attributed to potassium salts.	Verma & Banerjee (2012)
Advances in the formation and control methods of undesirable flavors in fish	Marine macroalgae used to reduce undesirable odors and tastes in fish.	Masking agents reduced muddy/earthy flavors in fish oil.	Wu et al. (2022)

Salt Reduction Strategies and Enhanced Saltiness Perception in Fish Products	Investigated the use of natural polysaccharide kappa-carrageenan, along with amino acids like arginine and histidine, as flavor enhancers in salt-reduced fish products. Sensory evaluations and chemical analyses were conducted to assess bitterness masking and overall flavor enhancement.	The combination of kappa-carrageenan with arginine and histidine effectively masked the bitterness associated with KCl, improving the sensory acceptance of salt-reduced fish products.	Zhang et al., (2024)
Mastering the art of taming: Reducing bitterness in fish by-products derived peptides	Study on bitterness reduction strategies using ultrafiltration and nanofiltration in seafood processing.	The combination of enzymatic hydrolysis and advanced filtration significantly reduced bitterness in seafood extracts.	Zhou, Y., et al., (2023)

6. ECONOMIC FEASIBILITY AND INDUSTRIAL SCALE-UP OF SODIUM REDUCTION TECHNOLOGIES

6.1. Sodium Reduction Technologies and Alternatives

6.1.1. Salt Substitutes and Flavor Enhancers

Potassium chloride (KCl) serves as the predominant salt substitute but can impart an undesirable metallic taste unless it is effectively masked or mixed (Nurmilah et al., 2022).

Amino acids such as lysine, arginine, and histidine can augment flavor in low-sodium formulations, yet their high ingredient costs pose challenges for large-scale application, particularly in products like processed meats (Fang & Zhu, 2025).

6.1.2. Microstructured Salts and Potassium/Magnesium Mixtures

Cutting-edge microstructured salts, exemplified by SODA-LO microspheres, along with sodium lactate, have demonstrated potential in smoked and fermented seafood throughout pilot studies (Bamaniya et al., 2024).

Blends enriched with potassium or magnesium can support sodium reduction in both processed and institutional food domains; however, their adoption is constrained by elevated retail costs and safety issues for at-risk groups, such as those vulnerable to hyperkalemia, particularly in low-income areas (Yin et al., 2021).

6.1.3. Innovative Processing Techniques

High-pressure processing (HPP), ultrasound-assisted brining, and fermentation methods present opportunities to lower sodium levels while preserving microbial safety and taste. Despite this, these techniques often require significant capital investment, increased energy consumption, and extended processing durations. The feasibility at an industrial level depends on pilot-scale validation across diverse seafood contexts (Loren et al., 2023).

In fish and seafood products, issues such as textural degradation and unpredictable sensory results have emerged during scaling, especially in restructured items, suggesting that technology must be customized for specific product types (Bamaniya et al., 2024).

6.2.Economic and Regulatory Factors

6.2.1. Cost-Benefit Modeling and Health Economics

From 2009 to 2018, broader reformulation efforts in the U.S. aimed at reducing sodium in packaged foods achieved an 8.5% sales-weighted reduction, but progress slowed once the more straightforward reductions had been implemented (Cogswell et al., 2021).

Economic models routinely show that mandatory or widely incentivized reductions in sodium (like 25–59% substitution) yield significant QALY enhancements and healthcare savings, far surpassing voluntary strategies (Nghiem et al., 2016; Smith et al., 1992).

6.2.2. Implementation Costs and Staged Reformulation

Estimates propose that aligning sodium reformulation efforts with regulatory guidelines could incur multibillion-dollar costs over a decade, but potential benefits from savings in healthcare and productivity could significantly offset these costs (Collins et al., 2019).

Adopting a tiered or gradual reformulation approach, which integrates new substitutes or processing techniques alongside scheduled equipment upgrades, could help manage capital expenses.

6.2.3. Policy and Market Incentives

Compulsory sodium reduction initiatives outclass voluntary ones in delivering extensive, long-term advantages (Nilson et al., 2022).

Government-imposed sodium targets, like those from WHO and FDA's voluntary guidance, stimulate R&D and the adoption of industry-wide practices (Rosewarne et al., 2022).

In the context of emerging economies, Kingwascharapong et al. (2024) highlighted how stealth sodium reduction approaches—such as flavor masking, consumer-driven prototyping, and formulation redesign—can be effectively adapted in regional industries with limited access to advanced processing technologies. Their study focused on the green mussel industry in Thailand and demonstrated that moderate sodium reduction (30%) achieved through tailored sensory engineering maintained consumer acceptability while enhancing nutritional profiles. They emphasized that successful adoption in low-resource settings requires not only technical feasibility but also investments in local capacity-building and adaptive consumer education programs (Kingwascharapong et al., 2024).

7. SECTOR-SPECIFIC OBSERVATIONS: SEAFOOD

Pilot trials within the seafood sector—especially in smoked and fermented products—have highlighted the potential for sodium replacement using ingredients like potassium chloride, sodium lactate, and microstructured salts. Nevertheless, restructured seafood seems to struggle with textural and sensory acceptance challenges during scaling (Bamaniya et al., 2024).

Emerging methods like HPP and ultrasound-assisted brining might mitigate sensory or safety trade-offs but necessitate additional energy and cost evaluations (Loren et al., 2023).

To ensure economic feasibility, industry-level implementation of salt replacement in seafood demands validation through pilot plant trials, cost-efficiency modeling, and consumer sensory testing, tailored to product types such as restructured versus intact seafood (Bamaniya et al., 2024).

8. SYNTHESIS AND PROSPECTS

Creating an economically feasible route for industrial sodium reduction in seafood and other food categories relies on:

- Technology alignment: Such technologies and methods must be optimized for specific products and senses.
- Economic considerations: Initial reformulation costs can be offset via healthcare savings, premium marketing for "low-sodium" options, and phased capital investments.

- Policy alignment: Voluntary reformulations alone have limited sustainability; mandatory or incentive-driven frameworks significantly boost effectiveness.
- Bridging pilot to industry: Successful scaling requires pilot data on costs, throughput, texture, flavor, and equipment impact to maintain feasible profit margins.

In conclusion, the most widely used and effective method for reducing sodium chloride in processed seafood is the addition of KCl, specifically substituting up to 50% of NaCl. However, higher levels introduce a bitter taste. Further studies suggest that the bitter taste may be masked or eliminated using appropriate masking agents and flavor enhancers.

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