

# Strategies and Technologies for Sodium Reduction in Processed Foods

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## ABSTRACT

Excessive sodium consumption is a major contributor to hypertension, cardiovascular disease, and other chronic health risks worldwide. While sodium plays critical roles in food--enhancing flavor, preserving quality, and influencing texture--modern intake levels far exceed physiological needs. Reducing sodium intake through reformulated foods is a key public health goal, yet presents technological and sensory challenges. This paper examines the physiology of salt taste perception, the health impacts of excess sodium, and current strategies to reduce sodium in processed foods. It reviews three primary approaches: the stealth reduction of sodium content, the use of salt alternatives such as potassium chloride (KCl), monosodium glutamate (MSG), and plant-derived seasonings, and advanced flavor enhancement technologies including salt microspheres, emulsions, and nanotechnology. Real-world examples demonstrate that significant sodium reduction can be achieved while maintaining consumer acceptance. Together, these innovations offer promising pathways to lower population sodium intake and improve cardiovascular health outcomes.

**Keywords:** Salt reduction; Sodium substitutes; Potassium chloride; MSG; Hypertension; Food chemistry; Flavor enhancement; Public health

## INTRODUCTION

Salt (sodium chloride) is a vital component of the human diet, essential for maintaining fluid balance, nerve signaling, and muscle contraction. However, modern diets are characterized by excessive sodium consumption, particularly through processed and convenience foods, such as meats, fast food, and instant noodles, and constitute a major public health concern (1).

High sodium intake is directly linked to increased blood pressure, which is a major risk factor for cardiovascular disease, the leading cause of death worldwide (2). Data from studies on diseases suggest that reducing dietary sodium could significantly lower hypertension rates and prevent thousands of cardiovascular-related deaths annually (3). Despite its risks, sodium plays a critical role in food production as it enhances flavor perception, preserves food, and affects texture in processed foods. Because of these functions, sodium reduction is a complex challenge that requires alternatives that can maintain the functional properties of salt while also minimizing health risks.

Given the urgent need to reduce sodium intake, an increasing amount of research has focused on

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identifying effective sodium alternatives.. Current studies have particularly concentrated on substitutes like monosodium glutamate (MSG), potassium chloride, and plant-derived seasonings, which aim to maintain flavor and texture while significantly reducing sodium. The present research aims to examine the physiology of salt taste perception, analyze the health impacts of excessive sodium intake, and evaluate current sodium reduction strategies. In particular, it focuses on the potential of potassium chloride, monosodium glutamate, and plant-derived seasonings to serve as effective salt alternatives while maintaining food quality and consumer acceptance.

## HEALTH EFFECTS OF SODIUM

Excessive salt intake has been associated with a wide range of health concerns beyond hypertension, including an increased risk of osteoporosis due to elevated calcium excretion, a higher incidence of gastric cancer, and kidney disease. In response, numerous global health initiatives aim to achieve at least a 30% reduction in sodium intake by 2025. Given the strong and well-documented relationship between sodium intake and hypertension, this section focuses primarily on the cardiovascular risks of excessive sodium consumption.

Global sodium consumption significantly exceeds recommended levels, posing a serious public health challenge. The World Health Organization (WHO) advises a maximum daily salt intake of five grams (equivalent to about two grams of sodium) (4). However, recent data reveal that most countries surpass this threshold by a wide margin. For instance, average salt intake ranges from 7.0 g/day in Ukraine to over 14 g/day in Hungary, with many developed nations like the United States and Canada averaging nearly 9 g/day or more (see Table 1). These figures underscore the global urgency of sodium reduction initiatives (4).

Extensive research highlights the severe health implications associated with high sodium diets, notably hypertension, stroke, and heart disease (2, 4). Hypertension alone affects an estimated 1.28 billion adults globally, particularly in low- and middle-income countries (5). Thereby, sodium significantly increases the risk of stroke, heart failure, and kidney diseases (2, 4). Further clinical evidence has linked sodium intake to increased blood pressure. The INTERSALT study, which includes data from over 10,000 people across 32 countries, found that populations consuming less

than three grams of sodium per day did not exhibit age-related increase in blood pressure. In contrast, populations with higher sodium consumption exhibited significant age-related increases in blood pressure (6).

Similarly, the Dietary Approaches to Stop Hypertension (DASH) trial found that reducing daily sodium intake from 3.4 grams to about 1.2 grams significantly decreased systolic blood pressure (i.e., the pressure in the arteries when the heart contracts) by approximately 6.7 mmHg in people following a typical diet. In people following a healthy diet rich in fruits, vegetables, and low-fat dairy products, an additional 3 mmHg reduction was observed (3). Globally, a reduction of 15% in salt intake could prevent approximately 8.5 million cardiovascular-related deaths over the course of ten years (2).

## TASTE PERCEPTION AND FUNCTIONAL ROLE OF SALT

Understanding how salt is perceived is essential for developing effective sodium reduction strategies. Humans exhibit both a biological and behavioral inclination toward salt. While sodium is physiologically required for nerve conduction, fluid regulation, and muscle contraction, cravings for salt often exceed biological need. Infants begin to show a preference for salty tastes as early as four months old, and these preferences are further shaped by early diet and cultural exposure (7, 8). Research also indicates that early-life sodium losses, such as through dehydration or illness, can lead to stronger salt cravings later in life,

**Table 1.** Average daily salt intake (g/day) in selected countries to WHO recommendation (5 g/day)

| Country | Avg Salt Intake (g/day) |
|---------|-------------------------|
| USA     | 8.9                     |
| Canada  | 9.1                     |
| UK      | 7.1                     |
| France  | 7.6                     |
| Germany | 8.7                     |
| Hungary | 14.3                    |
| Ukraine | 7.0                     |
| China   | 11.0                    |

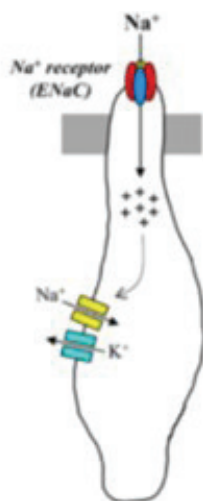
Data represent most recent estimates available as of 2024.

suggesting that the body learns to associate salt with recovery and survival (8).

The perception of saltiness is primarily triggered by sodium ions ( $\text{Na}^+$ ) entering taste receptor cells through epithelial sodium channels (ENaCs). These ion channels are particularly concentrated at the tip of the tongue and activate neural pathways that register saltiness in the brain (10). Figure 1 illustrates this mechanism, showing how sodium ions flow through ENaC channels to generate a neural signal interpreted as saltiness. This mechanism makes sodium an especially potent taste stimulus compared to other minerals like potassium or magnesium.

Salt's role in food extends well beyond taste. It enhances the overall flavor profile by suppressing bitterness, amplifying sweetness, and intensifying savory (umami) notes, especially when used in combination with ingredients like monosodium glutamate (MSG) (10). This synergistic effect is particularly valuable in sodium-reduction strategies that aim to preserve the appeal of processed and packaged foods.

Beyond flavor enhancement, sodium chloride plays a vital role in the physical and microbiological properties of food. It contributes to texture by influencing gluten development in dough, and it preserves shelf life by reducing water activity and inhibiting microbial growth. As such, reducing sodium content in food products is



**Figure 1.** Schematic of salt perception via ENaC channels on taste receptor cells. Sodium ions enter the channels, triggering a signal interpreted by the brain as salty taste. Adapted from Bigiani A. (9).

not simply a matter of removing salt, but rather requires holistic reformulation to maintain safety, structure, and consumer acceptability (1).

## NEED FOR ALTERNATIVES

Given the evident health risks associated with excessive salt consumption, there is a crucial need for effective and palatable salt substitutes. These substitutes must replicate the desirable flavor and functional properties of sodium chloride, as consumer acceptance is strongly dependent on maintaining taste and texture (11).

Sodium alternatives can be broadly categorized into three groups. Mineral-based substitutes, such as potassium chloride (KCl) and magnesium salts, aim to mimic the salty taste while reducing sodium content. Flavor-enhancing agents, such as monosodium glutamate (MSG) or yeast extracts, do not taste salty on their own but enhance umami and savory notes to compensate for lower salt levels. Finally, plant-derived seasonings, including garlic, onion, citrus, and herbs, introduce complex flavors that shift attention away from saltiness while contributing additional nutritional or antioxidant benefits (13).

While promising, these substitutes are not without challenges. Mineral salts like KCl can introduce bitterness or metallic aftertastes, particularly in delicate foods. MSG, despite regulatory approval and safety validation, continues to face public skepticism. Herbal blends, though flavor-rich, often suffer from batch inconsistency or shelf instability.

Current research highlights several promising candidates, including potassium chloride, MSG, and plant-derived seasonings, which have demonstrated potential both in sensory acceptance and health benefits, positioning them as valuable tools in addressing global sodium overconsumption (13). These strategies are explored further in Section 2, along with technologies that enhance flavor delivery in low-sodium formulations.

## STRATEGIES FOR SODIUM REDUCTION IN PROCESSED FOODS

Excessive salt consumption is a major contributor to the global burden of hypertension, cardiovascular disease, and other related health issues (4). In many developed countries, processed and packaged foods account for over 75% of total sodium intake. A wide variety of common foods contribute significantly to daily sodium intake, highlighting the need for such

regulations (see Table 2). Table 2 highlights the high sodium content in common packaged foods like canned soup, instant noodles, deli meats, and savory snacks, showing how everyday items can quickly add up and contribute substantially to daily intake. Given that modern diets heavily rely on processed and prepared foods that often contain high levels of sodium, strategies are required to address this issue. In particular, food manufacturers can play a crucial role in efforts to reduce population-level salt consumption. Reformulation is the process of modifying food product recipes to lower their sodium content without compromising taste, shelf life, or properties such as texture and microbial stability, defined as a product's ability to resist spoilage and maintain its quality over time (3). Efforts to reduce salt intake include the reformulation of processed foods, development of salt alternatives, and application of advanced food technologies that enhance flavor delivery while minimizing sodium content. Many of the most effective salt-reduction strategies combine several approaches together to achieve both health and sensory goals (3).

Reformulation of processed foods typically employs several complementary strategies to reduce sodium

content while maintaining product quality. These approaches can be grouped into three broad categories for discussion: (a) the stealth approach, which gradually reduces sodium over time to allow consumers to adjust; (b) the use of salt alternatives such as potassium chloride, MSG, and magnesium salts to replicate salty taste with less sodium; and (c) flavor enhancement technologies such as salt microspheres, emulsions, and nanostructured seasonings that intensify perceived saltiness without increasing sodium content.

### Stealth Approach

Governments and health organizations have implemented both voluntary and mandatory sodium reduction targets for key food categories such as bread, soup, ready meals, deli meat, and snacks. Voluntary programs include the United Kingdom's initiative, where the Food Standards Agency (FSA) established progressive sodium targets for over 80 food categories beginning in 2006. As a result, average adult salt intake in the UK declined from 9.5 g/day in 2003 to 8.1 g/day in 2011, a reduction of approximately 15% (3, 14). This success has been largely attributed to a "stealth" approach that gradually reduced sodium content over time, allowing consumers' palates to adapt without perceiving a sudden difference in taste (3).

In contrast, some countries have adopted mandatory sodium limits. For example, South Africa introduced legally mandated maximum sodium levels for several processed food categories in 2013, including bread, breakfast cereals, margarine, and processed meats (14). These regulatory approaches aim to drive more uniform and widespread sodium reductions across the food industry.

In Finland, sodium reformulation was supported through nationwide public education campaigns and mandatory front-of-package warning labels on high-sodium products. This multifaceted strategy contributed to a 3 g/day reduction in average sodium intake and a 75% decline in deaths from stroke and heart disease over a 30-year period (3).

While both voluntary and mandatory sodium reduction programs have shown success, their effectiveness can vary based on enforcement, industry compliance, and public awareness. Voluntary initiatives may suffer from inconsistent adoption, especially among smaller manufacturers without reformulation resources. Mandatory limits, while more uniform, require robust monitoring systems and may face pushback from industry stakeholders concerned about cost or product

**Table 2.** Sodium content of common processed foods, illustrating major contributors to daily intake. Values represent average sodium content per 100g or per serving size, depending on food type.

| Food Product                                 | Serving Size    | Sodium (mg) |
|----------------------------------------------|-----------------|-------------|
| Chicken noodle soup (canned, ready-to-serve) | 1 cup (240 mL)  | 867         |
| Cheese, parmesan, grated                     | 1 cup           | 1804        |
| Fast-food biscuit with egg and bacon         | 1 biscuit       | 1266        |
| Tomato sauce, canned with onions             | 1 cup           | 1350        |
| Ham, cooked, spiral-sliced                   | 1 slice (~28 g) | 1417        |
| Burrito (bean & cheese, fast food)           | 1 burrito       | 1040        |
| Breakfast cereal (e.g., Cheerios)            | 1 cup           | 213         |
| Deli turkey, sliced                          | 1 slice (~28 g) | 251         |
| Chips, potato, salted                        | 1 oz (~22g)     | 148         |

acceptability. Additionally, policy success often hinges on complementary strategies such as public education and front-of-package labeling, which help build consumer support for reformulated products. Without these supportive measures, even well-designed policies may fall short of their sodium reduction goals.

### **Salt Alternatives**

Salt alternatives represent another major strategy for reducing sodium intake. These alternatives attempt to replicate the sensory and functional qualities of sodium chloride (NaCl) using other compounds. The goal is to retain the saltiness and mouthfeel that consumers expect while lowering the total sodium load (13).

#### Potassium Chloride (KCl)

Potassium chloride is one of the most commonly used salt substitutes in commercial food products (12). It provides a salty flavor with no sodium, making it a potent option for sodium reduction. KCl is already used in various products such as reduced-sodium soups (11), processed meats, and cheeses (13). However, its application is limited by undesirable flavors such as bitterness and a metallic aftertaste. Studies have identified several strategies to overcome these drawbacks, such as blending KCl with masking agents (e.g., amino acids or flavor modulators), using encapsulation to delay its release, or balancing it with sodium chloride to dilute the bitterness while maintaining functionality (12).

KCl has shown promising results in real-world applications. For example, a study on sodium-reduced soups found that replacing up to 18% of sodium chloride with a mixture of KCl and MSG not only preserved but sometimes enhanced perceived saltiness and the consumer's liking (11).

However, the effectiveness of these strategies can vary by product type, and bitterness remains a major obstacle in delicate or low-fat foods where strong off-flavors are harder to mask. Additionally, consumer rejection of metallic or "chemical" tastes has been reported in blind sensory panels, especially among individuals unaccustomed to potassium-based ingredients. This suggests that more research is needed to standardize masking approaches across diverse food matrices and cultural palates.

#### Monosodium Glutamate (MSG)

Although it contains sodium, monosodium glutamate (MSG) contributes significantly less sodium

per gram than sodium chloride. Specifically, MSG is approximately 12% sodium by weight, compared to 39% sodium in NaCl (13, 11), meaning it delivers about three times less sodium per gram. MSG is an effective enhancer of umami flavor, which has been shown to increase the overall perception of saltiness and savory depth (11). Including MSG in salt-reduced products allows for a reduction in NaCl while maintaining or even improving taste. Furthermore, MSG has been shown to suppress bitterness, which is a useful trait when used alongside potassium chloride (11).

Despite public skepticism, for example, surveys show that many consumers mistakenly associate MSG with negative health effects such as "Chinese Restaurant Syndrome" or view it as an artificial additive (11), MSG is recognized as safe by major health agencies, including the U.S. Food and Drug Administration (FDA), the European Food Safety Authority (EFSA), and the World Health Organization (WHO) (11, 13). It is also naturally present in a variety of fermented and protein-rich foods, such as Parmesan cheese, soy sauce, tomatoes, and mushrooms (13). When carefully dosed and paired with other salt substitutes, MSG can help facilitate sodium reductions of up to 30% or more without negatively impacting consumer preference (13).

However, its effectiveness can depend on the type of food, as MSG performs best in umami-rich matrices like soups and broths but is less impactful in dry or sweet products. There is also regional variation in consumer attitudes—while MSG is widely accepted in many Asian cuisines, Western markets continue to show hesitation despite regulatory approvals. This gap highlights the importance of consumer education and transparent labeling in ensuring public confidence in sodium-reduction strategies that rely on MSG.

#### Other Mineral and Herbal Salt Substitutes

In addition to KCl and MSG, some salt alternatives are enriched with minerals such as magnesium, lysine, and trace elements. One animal study using a potassium- and magnesium-enriched salt blend demonstrated that this formulation prevented cardiac hypertrophy (enlargement of the heart) and inhibited blood pressure increases in hypertensive rats (15). These findings suggest that such blends may offer both sensory and potential health advantages over traditional salt.

Another growing segment of salt substitutes involves the use of plant-derived flavorings and spice blends. Products such as Mrs. Dash and McCormick salt-free blends use herbs, citrus, and umami-rich vegetables

to replicate or enhance savory flavor without sodium (16). A recent review by Taladrid et al. summarized approximately 15 studies, including sensory panel studies with 20 to 50 participants, which found that blends containing garlic, onion, saffron, hot spices, and grape-derived extracts can serve as effective salt replacers. In addition to enhancing flavor, these plant-based ingredients can contribute beneficial antioxidants and bioactive compounds (17).

These alternatives are particularly important for consumers with medical restrictions, such as those with chronic kidney disease, who need to avoid both sodium and potassium. For these people, sodium-free and potassium-free herbal seasoning blends provide a safe, flavorful option (17).

However, many plant-based blends are highly product-specific and may not translate well across food types. Their volatile flavor compounds can degrade during cooking, limiting shelf stability, and some spices may introduce allergen or sensitivity concerns. Additionally, formulation consistency and intensity of flavor vary between commercial blends, complicating their use in standardized large-scale manufacturing. More research is needed to optimize their flavor delivery and ensure reproducibility across production batches.

### Flavor Enhancement Technologies

Advanced food science techniques are being employed to improve the effectiveness and consumer acceptance of salt reduction. These methods involve restructuring salt or enhancing flavor release during consumption. Key approaches include the use of salt microspheres to increase surface area and perceived saltiness, emulsions that control the release of salt compounds, and nanostructured seasonings designed to optimize flavor delivery while minimizing sodium content (17, 18, 19).

### Salt Microspheres and Crystal Engineering

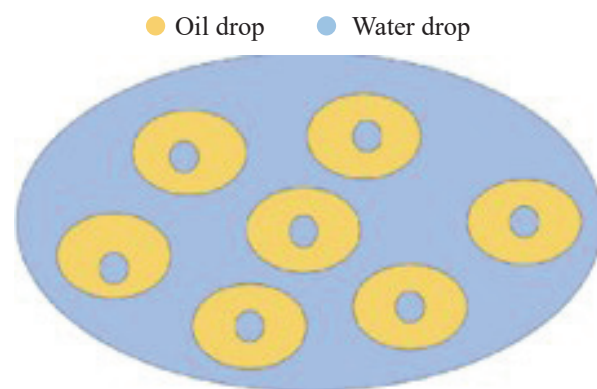
New ingredient technologies have also made reformulation more viable. In bread and bakery applications, for example, researchers have tested hollow salt microspheres, which are engineered particles with greater surface area and faster dissolution. By coating food more uniformly and dissolving rapidly in saliva, these microspheres can significantly reduce sodium content without diminishing perceived saltiness (18). When incorporated into dough, they have been shown to deliver comparable flavor intensity with up to 40%

less sodium than conventional salt, while preserving dough structure and fermentation performance (18). Such innovations complement broader public health strategies for sodium reduction, which also include reformulating processed foods, educating consumers, improving food labeling, and establishing sodium targets for the food industry (3).

Despite their promise, microspheres are still in early stages of commercial adoption, partly due to their production cost, complexity of incorporation into varied food matrices, and regulatory uncertainty in some markets. Additionally, their effectiveness depends on precise particle size and dissolution timing, which can be difficult to optimize across different moisture levels and textures. These challenges may limit their application in small-scale food production and non-uniform or artisanal products.

### Emulsion and Nanotechnology-Based Systems

Flavor encapsulation in emulsions (such as water-in-oil-in-water systems) allows for gradual, targeted release of salty or savory flavors during mastication, or while chewing. These systems can be tuned to release salt at the time when it is most perceptible, optimizing flavor perception with less sodium. Figure 2 illustrates this concept, showing how the structure of the emulsion is designed to release flavor during chewing, delivering a burst of saltiness right when it's most noticeable. This encapsulation system is particularly useful in complex dishes like soups, sauces, and meat, because these



**Figure 2.** Schematic of a water-in-oil-in-water (W/O/W) emulsion system designed to enhance saltiness perception. The encapsulated salt is protected during cooking and releases a targeted burst of flavor during mastication (chewing), maximizing perception with less sodium. This system is especially beneficial for complex food matrices such as soups and sauces.

foods often have a mix of textures, high moisture, and bold flavors that benefit from controlled flavor release. Water-in-oil-in-water emulsions help protect salt and savory compounds during cooking and storage, and then release them gradually during eating. This allows for a more noticeable burst of saltiness at the right moment, helping to maintain flavor while reducing overall sodium content (19).

Nanotechnology introduces innovative methods for enhancing flavor by encapsulating salt and other taste compounds in nanoparticles or ultra-thin layers. These delivery systems can be designed to release flavor either in a quick burst or more gradually, syncing with the way we chew and experience food. This not only boosts flavor perception but also allows for less sodium per bite. Similarly, layered seasoning techniques can stagger the release of different flavor components, helping to sustain a rich, savory taste throughout the entire eating experience (19, 20).

However, many of these technologies remain

confined to research or pilot-scale settings, and their integration into industrial food production faces key challenges. Emulsion systems can be unstable during long-term storage or thermal processing, requiring precise formulation and packaging conditions. Similarly, nanotechnology applications may raise regulatory and consumer concerns, particularly around labeling, safety transparency, and cost. While promising, further work is needed to validate these approaches across diverse food categories and ensure scalability for widespread use.

A comparative overview of major sodium reduction strategies is presented in Table 3, summarizing their mechanisms, benefits, limitations, and real-world examples.

### EXEMPLARS OF SODIUM REDUCTION IN FOOD ACROSS THE GLOBE

To address public health concerns over high sodium intake, the food industry has implemented a variety of

**Table 3.** Comparative overview of sodium reduction strategies used in the food industry. This table summarizes the mechanism, benefits, limitations, and real-world applications of various approaches to reduce sodium content in processed foods (3, 11, 13).

| Strategy/Technology        | Mechanism                                                  | Benefits                                    | Limitations                              | Examples/Case studies                   |
|----------------------------|------------------------------------------------------------|---------------------------------------------|------------------------------------------|-----------------------------------------|
| Potassium Chloride (KCl)   | Replaces NaCl with KCl to mimic saltiness                  | No sodium; retains salty taste              | Can have bitter/metallic aftertaste      | Used in soups, meat products, cheese    |
| Monosodium Glutamate (MSG) | Enhances umami to boost salt perception                    | Lower sodium by weight; boosts flavor       | Consumer skepticism; additive stigma     | Used in soups, savory snacks            |
| Plant-Based Seasonings     | uses herbs/spices to add flavor complexity                 | Natural; adds antioxidants and bioactives   | Flavor inconsistency; limited shelf life | Mrs. Dash, McCormick salt-free blends   |
| Salt Microspheres          | Increases surface area to enhance salty perception         | Up to 40% sodium reduction possible         | Requires formulation expertise           | Bread dough with hollow salt spheres    |
| Flavor Emulsions           | Timed release of salt during chewing                       | Maintains flavor while lowering sodium      | Complex formulation; costlier            | Water-in-oil-in-water systems in sauces |
| Nanotechnology Delivery    | Encapsulates salt for burst or staggered release           | Precise control of salt delivery            | Requires advanced tech & R&D             | Layered seasonings in savory foods      |
| Stealth Reformulation      | Gradually lowers sodium in food without consumer awareness | High consumer acceptance; unnoticed         | Requires product-specific tuning         | UK cereals Campbell's tomato soup       |
| Mandatory Sodium Limits    | Legal sodium limits on processed foods                     | Population-wide impact; industry compliance | Enforcement and monitoring required      | South Africa food categories (2013)     |

reduction strategies, most commonly the stealth approach. A prominent example of this is Campbell's condensed tomato soup, which was reformulated using stealth reduction to decrease sodium content from 573 mg to 427 mg per 100 g, a 25.5% reduction, while maintaining its unique flavor and consumer acceptance (1).

In Uruguay, researchers applied a similar stealth method to reduce salt in bread. Consumers were not told of the changes, and sodium was gradually decreased over time. This approach was effective: participants continued to rate the bread favorably, demonstrating that reformulation can be successful (21). The United Kingdom's breakfast cereal sector achieved substantial sodium reductions, ranging from 12% to 88%, through gradual product reformulation. This strategy involved rebalancing flavor profiles and optimizing recipes to lower sodium levels while retaining the familiar taste and texture consumers expect from cereal products (22).

In the snack food industry, PepsiCo announced a sodium reduction initiative for Lay's Classic Potato Chips in the U.S. market, aiming to cut sodium by 15% (from 170 mg to 140 mg per serving) (23). While the company has not disclosed precise formulation details, it is suggested that PepsiCo utilized engineered salt crystals, such as hollow salt microspheres or reduced-size crystals with greater surface area, to enhance saltiness perception at lower doses (23). PepsiCo has also set broader global sodium reduction targets across its snack portfolio by 2025, with implementation varying by region (24).

These examples highlight how everyday foods, like soup, bread, chips, and breakfast cereals, have undergone effective sodium reduction without turning consumers away. Despite reformulation, these products remain staples in many households, demonstrating changes can be made without disrupting consumer satisfaction or market success.

## LIMITATIONS AND CHALLENGES IN SODIUM REDUCTION STRATEGIES

Despite promising advancements in salt reduction technologies and alternatives, several challenges hinder their widespread adoption and long-term success.

### Sensory and Functional Trade-Offs

One of the most significant limitations is the unfavorable taste profile of many sodium alternatives. Potassium chloride (KCl), while effective in mimicking saltiness, often introduces bitterness or metallic

aftertastes, particularly noticeable in low-fat or delicately flavored foods. Although masking agents and blends with sodium chloride can mitigate this issue, results vary significantly across food matrices, and full sensory equivalence remains elusive. Similarly, monosodium glutamate (MSG) enhances umami and suppresses bitterness but is less effective in sweet or dry products, and its reputation suffers from longstanding consumer misconceptions despite scientific safety validation.

### Technological and Scalability Barriers

Emerging technologies such as hollow salt microspheres, flavor emulsions, and nanostructured delivery systems show strong potential to enhance perceived saltiness at lower sodium levels. However, their commercialization is limited by high production costs, complex formulation requirements, and lack of scalability, especially for small- and medium-sized food manufacturers. Many of these innovations remain confined to laboratory or pilot-scale trials, with limited real-world validation across diverse food categories.

### Consumer Acceptance and Cultural Variation

Consumer response to sodium reduction strategies is not uniform. Cultural preferences, habitual taste expectations, and skepticism toward unfamiliar ingredients (e.g., MSG or magnesium salts) can hinder adoption. For example, MSG is widely accepted in Asian cuisines but often rejected in Western markets due to outdated safety concerns. Similarly, plant-based seasoning blends, though appealing for health-conscious consumers, are often product-specific and may degrade in flavor during cooking or storage.

### Policy, Regulation, and Industry Compliance

Voluntary reformulation programs, while beneficial, often face uneven implementation and lack enforceability. Mandatory sodium limits, such as those implemented in South Africa or Argentina, require robust monitoring systems and may face resistance from industry stakeholders. The success of regulatory frameworks also hinges on supportive measures, such as consumer education, front-of-package labeling, and fiscal incentives for reformulation, which are not universally present. Inconsistent global policies make it difficult to establish clear benchmarks or collaborative standards.

### Gaps in Long-Term Data

Many studies focus on immediate sensory outcomes or short-term clinical trials. However, there is limited

longitudinal data on how sodium reduction strategies impact consumer behavior, repeat purchase decisions, or real-world health outcomes. It remains unclear whether initial reductions in sodium translate to lasting public health improvements without accompanying policy, education, and access efforts.

## CONCLUSION

Reducing dietary sodium remains a global public health imperative, given its strong association with hypertension, cardiovascular disease, and stroke. While sodium plays critical roles in food, such as enhancing taste, ensuring preservation, and contributing to texture, modern consumption levels far exceed physiological needs and continue to rise in many populations.

This review has examined multiple sodium reduction strategies across sensory science, ingredient innovation, and food processing technologies. Among the most promising are multi-pronged approaches that integrate gradual stealth reduction, functional substitutes like potassium chloride, MSG, and plant-based seasonings, and advanced delivery systems such as microspheres, emulsions, and nanotechnology. These strategies show measurable success in reducing sodium without significantly compromising flavor or consumer acceptance.

However, key challenges remain. Salt substitutes often come with off-flavors or consumer skepticism, especially in culturally sensitive markets. Technological solutions face hurdles in scalability and cost-effectiveness. Policy efforts vary widely across regions, and real-world adoption is inconsistent without regulatory pressure or public education. Moreover, long-term data on behavior change, product reformulation durability, and health outcomes are still limited.

To accelerate progress in this field, future research should prioritize the development of multi-ingredient formulations that not only reduce sodium but also maintain sensory appeal and functional performance. It will be important to conduct longitudinal consumer testing across diverse demographics and food systems to better understand acceptance and long-term impact. Researchers should also evaluate the stability and safety of emerging salt substitutes under real-world commercial processing and storage conditions. Finally, meaningful progress will require policy integration, including clear sodium labeling, reformulation incentives for industry, and consistent public health messaging to guide consumer choices. Ultimately,

the success of sodium reduction efforts depends on collaborative action—bridging flavor science, nutrition research, food industry innovation, and public policy. By uniting these sectors, the global food system can transition toward healthier, lower-sodium products that retain both consumer appeal and public health value.

## CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this article.

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