

Review

Sodium Reduction in Traditional Fermented Vegetables: Challenges, Strategies, and Perspectives

Mingzhu Li, Hongchen Fan * and Mingshou Lü * 

College of Food Engineering, Harbin University of Commerce, Harbin 150028, China; zy_mingzhu@163.com

* Correspondence: fanhongchen@hrbcu.edu.cn (H.F.); lumingshou@hrbcu.edu.cn (M.L.)

Abstract

Sodium salt is critical for determining the quality of fermented vegetables, with particular influence on their physicochemical properties, textural characteristics, and food safety. However, the relatively high salt levels in traditional fermented products do not align with the growing consumer preference for low-salt, health-oriented foods. Simply reducing salt levels compromises the storage stability, edibility, and processability of fermented vegetables. Therefore, lowering salt content while maintaining product quality poses a significant challenge for the fermented vegetable industry. Effective quality control in low-salt fermented vegetable production requires a comprehensive understanding of the role salt plays in product quality. In this review, we outline the functions of salt in fermented vegetables and detail the current applications and technological developments in salt-reduction strategies; we focus on sodium substitutes, biological salt-reduction approaches, and emerging non-thermal technologies. The current challenges in low-salt fermentation processes are also discussed, providing valuable theoretical and practical guidance for the high-quality processing of low-salt fermented vegetable products.

Keywords: fermented vegetables; reducing sodium salt; biological salt-reduction strategies

1. Introduction

With a long history of production, traditional fermented vegetables—such as Chinese suancai and paocai, Korean kimchi, European pickled cucumbers, and table olives—are enjoyed worldwide for their distinct flavors and nutritional value, and have become a staple in diets globally. Depending on variations in raw materials, environmental conditions, and processing methods, common varieties like sauerkraut and pickles are typically produced from vegetables such as cabbage, radish, kale, mustard, chili peppers, cucumbers, and olives (Figure 1A) [1]. Owing to the essential role of salt in flavor formation, color, texture preservation, and long-term storability, most traditionally fermented vegetables contain high levels of salt [2].

Salt is an essential nutrient for maintaining human fluid balance, cellular function, and nerve transmission. However, excessive salt intake is strongly linked to hypertension, cardiovascular diseases, stroke, kidney disease, gastric cancer, osteoporosis, and obesity (Figure 1B). The World Health Organization (WHO) recommends that adults limit daily salt intake to less than 2 g (equivalent to 5 g of salt). However, most traditional fermented vegetables typically contain 2–8% (*w/w*) salt, resulting in a substantially higher salt intake when consumed regularly. This discrepancy highlights the urgent need for effective salt-reduction strategies in fermented vegetable production. In recent years, high dietary salt consumption has emerged as a major public health issue, exacerbated by increasing

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consumption of processed foods. Processed foods constitute the primary source of salt in the human diet, accounting for approximately 70–75% of total intake. Fermented vegetables, due to their high salt content, may pose considerable health risks, particularly in regions where they are consumed frequently as staple side dishes, constituting a significant proportion of daily salt intake. In many developing countries, traditional dietary patterns and limited cold-chain infrastructure increase reliance on salt-based preservation methods, thereby elevating overall salt exposure [3]. High salt concentrations present significant challenges in the production of traditional fermented vegetables. A high-salt environment inhibits the activity of key microorganisms, delaying acid production and flavor development from raw vegetables, and significantly extending the fermentation period, thereby increasing production costs. Moreover, the manufacturing process generates large volumes of high-salinity wastewater. This not only incurs high treatment costs but can also lead to environmental issues such as soil salinization, reduced soil productivity, and a loss of biodiversity. Consequently, particularly in response to growing public health concerns regarding hypertension and cardiovascular diseases, substantial research efforts have been devoted to developing low-salt fermented vegetables. A major challenge for the industry lies in reducing salt levels while preserving product safety and flavor quality. It should be noted that the term “low-salt” in this context is used in a relative sense, as salt concentrations vary widely among fermented vegetable products. In many traditional products, salt levels commonly range from 6% to 10%, and concentrations around 5% are therefore often described in the literature as reduced-salt formulations rather than strictly “low-salt” according to regulatory definitions [4].

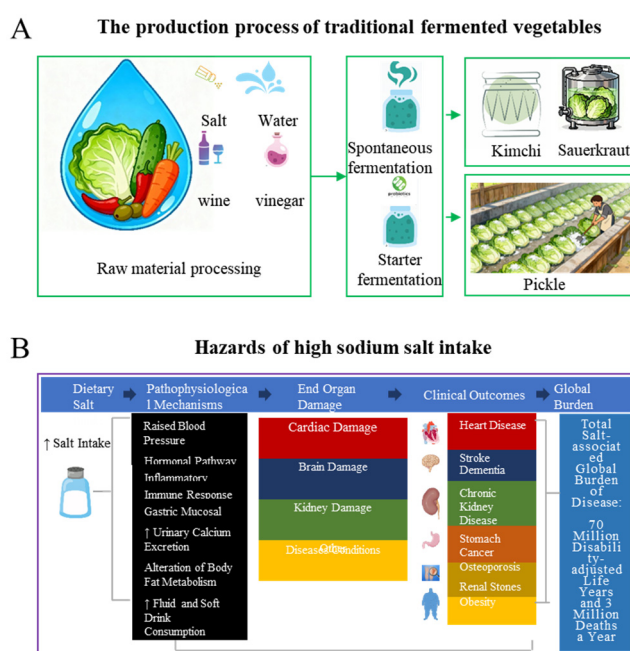


Figure 1. Production process, global salt distribution, and health risks associated with fermented vegetables. (A) The production process of traditional fermented vegetables [1]. (B) Hazards of high salt intake [5].

This review aims to consolidate the key information on salt reduction in fermented vegetables, supporting evidence-based strategies for adopting salt reduction in fermented foods as a part of sustainable food systems. The article addresses several key themes: the functional role of salt in fermented vegetables, the challenges associated with salt reduction in traditional products, current and emerging strategies for lowering salt content, and future prospects for the development of low-salt fermented vegetables.

2. The Role of Salt in Fermented Vegetables

Building on the public health and technological challenges associated with high salt levels, as discussed above, this section focuses on the mechanistic roles of salts in fermented vegetable systems. Specifically, we summarize how salts regulate microbial community structure, metabolic activity, and product quality during fermentation. Salt is a central regulatory factor in vegetable fermentation because it simultaneously controls water activity, osmotic pressure, ionic stress, and microbial selection. Through these physicochemical and biological effects, salt directly influences fermentation kinetics, microbial succession, and the formation of flavor and texture characteristics in the final product (Figure 2).

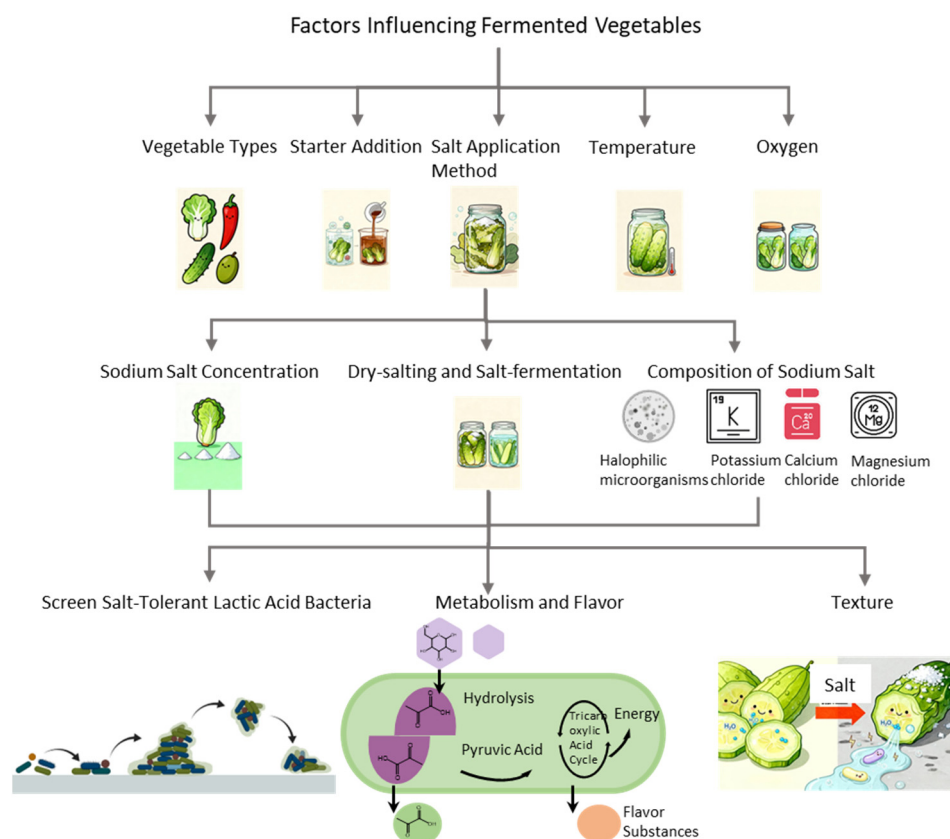


Figure 2. Mechanistic framework illustrating how salt-related factors shape microbial selection, metabolism, and quality formation in fermented vegetables.

2.1. The Impact of Salt Concentration in Fermented Vegetables

Salt concentration is a key determinant of the physical properties, sensory characteristics, and shelf life of fermented vegetables. During fermentation, salt helps in maintaining product quality by regulating water activity and osmotic pressure, thereby inhibiting harmful microorganisms and promoting the dominance of lactic acid bacteria (LABs) and yeasts, which constitute the core microbial consortium in vegetable fermentation. This salt-dedicated microbial selection constitutes a crucial stage in the vegetable fermentation process [6]. Extensive research has been conducted on the role of salt in fermented vegetables, with particular focus on its effects on bacterial community structure, metabolic activities, and flavor development at different concentrations. Commonly assessed parameters include pH, total acidity, LAB counts, volatile flavor compounds, taste-related components, spoilage and pathogenic microorganisms, and antioxidant properties (Figure 3).

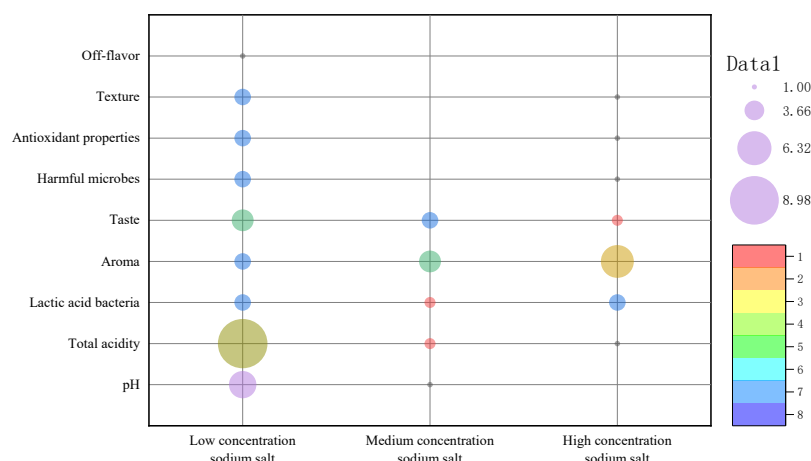


Figure 3. Comparative visualization of salt regulation in key fermentation parameters. This bubble plot illustrates different regulatory intensities: low (≤ 50 g/kg), medium (50–100 g/kg), and high (≥ 100 g/kg). Effect of NaCl concentrations on fermentation indicators including pH, total acidity, LAB abundance, flavor compound diversity, and suppression of harmful microorganisms. Bubble size reflects the relative magnitude of the reported effect, and the color gradient indicates the direction and intensity of regulation based on synthesis of the literature.

Salt content varies widely among different types of fermented vegetables, with reported concentrations ranging from 0 to 250 g/kg depending on product type. Representative concentrations are as follows: fermented chili peppers (20–240 g/kg), suancai (0–90 g/kg), paocai (30–250 g/kg), kimchi (0–50 g/kg), olives (60–80 g/kg), and fermented cucumbers (20–80 g/kg). For clarity and comparative discussion in this review, salt levels are categorized as low (≤ 50 g/kg), medium (50–100 g/kg), and high (≥ 100 g/kg), based on commonly reported values across representative products.

As summarized in Table 1 and illustrated in Figure 3, salt concentration exerts a concentration-dependent regulatory effect on microbial dynamics and flavor formation during fermentation. Under controlled fermentation conditions where LABs rapidly establish ecological dominance, low-salt environments (≤ 50 g/kg) often accelerate LAB proliferation and metabolic activity, resulting in enhanced production of organic acids, amino acids, and volatile flavor compounds. However, this positive effect is highly dependent on successful microbial succession during early fermentation.

Medium salt levels (50–100 g/kg) exhibit intermediate effects. While LAB proliferation and acid production are moderately supported, the overall metabolic intensity and flavor compound accumulation are lower than those observed under low-salt fermentation.

In contrast, high salt concentrations (≥ 100 g/kg) impose osmotic stress on microbial cells, restricting metabolic activity and slowing acid production. This often results in reduced LAB populations and limited synthesis of flavor compounds. Although high-salt environments may suppress the growth of spoilage and pathogenic microorganisms, they are generally less favorable for active fermentation and complex flavor development.

Notably, while low-salt fermentation promotes desirable LAB dominance and flavor enhancement, it may also increase the risk of harmful microbial proliferation if initial raw material hygiene is insufficient or if indigenous LABs fail to rapidly establish ecological dominance during early fermentation. Therefore, the outcome of low-salt fermentation is highly dependent on microbial succession dynamics and process control. Maintaining a balanced and stable beneficial microbial community is essential to ensuring both safety and quality throughout fermentation [7,8]. During fermentation, LABs produce a range of bioactive metabolites, including organic acids (e.g., lactic acid and acetic acid), bacteriocins, exopolysaccharides, bioactive peptides, short-chain fatty acids, and signaling molecules

involved in microbial communication. These metabolites have been widely reported to exhibit antimicrobial activity and to modulate gut microbiota, contributing to potential health-promoting effects [9].

Table 1. Effects of salt concentration on fermented vegetables.

Types of Fermented Foods	Region	Salt Concentration	Product Characteristic	Reference
Pepper	China	2–10% (wt/wt)	Increasing the salt concentration resulted in a higher pH and lower total acidity; the 6% sample exhibited the highest odor and taste scores, while the 8% and 10% samples received the highest texture scores.	[10]
Peppers	China	9–24%	The 24% salt treatment showed diminished microbial diversity, leading to rapid pH reduction and an earlier TTA peak (3.54 g/kg at 60 d). In contrast, the 9% salt group exhibited slower acidification, with a higher final TTA (2.58 g/kg at 90 d) and accelerated lactic acid accumulation. Texturally, the 9% group was significantly softer and less viscous, elastic, and chewy than the 24% group, despite similar soluble protein contents. Metabolically, the 9% group had higher free amino acid levels and enhanced carbohydrate metabolism, while the 24% group was enriched in amino acid metabolism. Sensorily, the 9% group displayed superior aromatic potential, whereas the 24% group had a slightly stronger saltiness perception.	[11]
Peppers	China	6–18% (wt/wt)	Lower salinity levels (6% and 9%) were associated with higher total acid content and greater bacterial diversity, as well as a more complex microbial community structure. In contrast, high salinity (12%) reduced microbial richness and diversity but effectively inhibited harmful microorganisms. Pathogenic bacteria were detected in the medium- and low-salinity samples, whereas their total relative abundance was suppressed at approximately 12% salinity. Therefore, salinity of 12% (<i>w/w</i>) is recommended for preservation, as it controls pathogenic bacteria without unduly inhibiting potentially beneficial bacteria.	[12]
Peppers	China	2–10%	Samples with lower salt content (2%) exhibited the lowest pH (3.77) and the highest total acid content, yet they received the lowest overall sensory scores. In contrast, higher salt content (10%) resulted in a significantly higher pH (3.89, $p < 0.05$) and lower acidity. An inverse relationship was observed between salt concentration and several biochemical indicators: increasing salinity led to a significant decrease in amino acid nitrogen content (from 0.091 g/100 g at 2% to 0.04 g/100 g at 10%) and markedly reduced the counts of total aerobic bacteria and lactic acid bacteria (LABs). Regarding volatile compounds, medium salt concentrations (8–10%) promoted the synthesis of key flavor substances, such as aromatic compounds and propanol, whereas esters were the dominant volatiles in low-salt samples (2–4%). Sensorily, the sample with 6% salt received the highest scores for odor and taste, while those with 8% and 10% salt were preferred for their texture.	[10]

Table 1. Cont.

Types of Fermented Foods	Region	Salt Concentration	Product Characteristic	Reference
Suancai	China	0–9% (wt/wt)	Regarding physicochemical properties, suancai fermented with 6% salt showed the lowest pH and the highest levels of total titratable acidity (TTA) and lactic acid (LA) at the end of fermentation. Although salt concentration modulated microbial community structure, it did not markedly influence the overall growth of <i>Lactobacillus</i> , which remained the predominant genus across all treatments; however, its relative abundance was lowest in the 9% salt group at the final stage. In contrast, several bacterial and fungal genera, including <i>Pediococcus</i> , <i>Leuconostoc</i> , <i>Weissella</i> , <i>Sporobolomyces</i> , <i>Azospirillum</i> , <i>Klebsiella</i> , <i>Acinetobacter</i> , and <i>Cladosporium</i> , were significantly affected by salt levels. Salt concentration also shaped volatile compound (VC) profiles during fermentation, with higher salinity leading to reduced isothiocyanate content. Correlation analysis further indicated a strong association between <i>Lactobacillus</i> abundance and volatile compound formation. Overall, the 6% salt treatment yielded the most favorable fermentation quality under the conditions tested.	[13]
Suancai	China	0.47–2.11%	The sample with 2.11% salt exhibited a markedly lower pH (3.63 ± 0.17) compared to the 0.47% salt sample (3.99 ± 0.35) ($p < 0.01$), which corresponded with significantly higher contents of titratable acidity (TTA) and lactic acid (LA). In contrast, glucose levels and microbial alpha diversity (as indicated by OTU numbers and the Shannon index) showed no significant variation between the two salt concentrations. <i>Lactobacillus</i> was the predominant biomarker in the 0.47% salt sample, whereas the 2.11% salt sample was characterized by biomarkers such as <i>Pediococcus</i> , <i>Clostridium sensu stricto</i> 11, <i>Acetobacter</i> , and <i>Vibrio</i> . Volatilomic analysis further revealed that the concentrations of key flavor compounds—including alcohols, aldehydes, phenols, ketones, sulfides, and heterocyclic compounds—were significantly elevated in the 2.11% salt sample.	[14]
Sauerkraut	China	0–3.5%	A salt concentration of 2.5% effectively accelerated maturation and optimized sugar utilization, thereby striking an optimal balance for promoting LAB metabolism, enriching flavor profiles, and ensuring the safety of the fermented vegetables.	[15]
Sauerkraut	China	2–8%	A 5% salt concentration was identified as optimal, as it effectively inhibited harmful microorganisms. In contrast, a lower concentration (2%) accelerated maturation but provided insufficient microbial safety, whereas a higher concentration (8%) delayed the process and impaired sugar metabolism, hindering the competitive exclusion of pathogens.	[16]

Table 1. Cont.

Types of Fermented Foods	Region	Salt Concentration	Product Characteristic	Reference
Paocai	China	3–9% (<i>w/v</i>)	Salt concentration had a profound influence on the fermentation dynamics and final product quality of paocai. Samples with higher salt content ($90 \text{ g}\cdot\text{L}^{-1}$) exhibited the most pronounced acidification, reaching the lowest final pH and the highest accumulation of titratable acidity (TTA) and lactic acid (LA). In contrast, the increase in TTA was more moderate in samples with lower salt concentrations (30 and $60 \text{ g}\cdot\text{L}^{-1}$). A positive correlation was observed between salt concentration and bacterial diversity. The relative abundance of <i>Lactobacillus</i> increased progressively with salinity, becoming the dominant genus during the middle and late fermentation stages, with its peak abundance observed at $60 \text{ g}\cdot\text{L}^{-1}$. Distinct microbial biomarkers were identified for each salt level: <i>Lactococcus</i> was associated with $90 \text{ g}\cdot\text{L}^{-1}$, while <i>Leuconostoc</i> and <i>Psychrobacter</i> were the biomarkers for $60 \text{ g}\cdot\text{L}^{-1}$. The volatile profile was similarly shaped by salt concentration. Higher levels of alcohols and aldehydes were detected in the 30 and $60 \text{ g}\cdot\text{L}^{-1}$ samples, whereas acids predominated at $90 \text{ g}\cdot\text{L}^{-1}$. Sensorily, the $30 \text{ g}\cdot\text{L}^{-1}$ sample scored lowest in sourness and astringency but highest in saltiness, while the $90 \text{ g}\cdot\text{L}^{-1}$ sample exhibited the most intense sour and astringent tastes.	[17]
Paocai	China	0.13–15.41%	The bacterial assembly in paocai fermentation was driven sequentially: by NaCl and then by acidity. Initially, NaCl selected for salt-tolerant <i>Leuconostoc mesenteroides</i> over the more sensitive <i>Lactococcus lactis</i> . As TTA accumulated, acid-tolerant <i>Lactobacillus</i> and <i>Pediococcus</i> outcompeted acid-sensitive genera. Further increases in acidity exerted species-specific inhibition, with <i>Lactobacillus buchneri</i> and <i>Pediococcus ethanolidurans</i> persisting after <i>Lactiplantibacillus plantarum</i> was suppressed.	[18]
Rape moss	China	6–8% (<i>wt/wt</i>)	Increasing salt concentration from 6% to 8% resulted in a gradual decline in flavonoid content in fermented rape moss (FRM) compared with the fresh material, whereas total phenols exhibited an overall increasing trend. Nitrite levels remained stable across this salinity range. In contrast, protein and fat contents decreased significantly ($p < 0.05$) with higher salt addition, suggesting suppression of microbial activity under osmotic stress. Antioxidant capacity showed an initial increase followed by stabilization, with no significant difference after the initial rise ($p > 0.05$); the highest value was observed at 7% salt.	[19]
Brassica napus	China	4–8% (<i>wt/wt</i>)	The sample with 8% salt exhibited the highest contents of titratable acidity (TTA), soluble sugar, and nitrite. The amino acid nitrogen content followed a unimodal trend, peaking at $2.01 \text{ g}/100 \text{ g}$ with 6% salt. In contrast, total phenol content initially decreased, reaching a minimum of 3.49 mg/g with 7% salt, before increasing again at 8% salt,	[20]

Table 1. Cont.

Types of Fermented Foods	Region	Salt Concentration	Product Characteristic	Reference
Brassica napus	China	4–8% (wt/wt)	potentially due to the accumulation of specific phenolic monomers. The 6% salt sample possessed the highest total free amino acid (FAA) content and was particularly abundant in sweet-tasting amino acids (15.02 mg/g), such as Asp, Glu, Gln, and Pro. Conversely, bitter-tasting amino acids were most prominent in the 8% salt sample. Volatile compound analysis revealed distinct profiles: the 4% salt sample was rich in alcohols (notably 6.88% phenylethyl alcohol), the 5% salt sample in pyrazines (10.40% trimethylpyrazine), and the 6% salt sample in ketones (40.72% total, dominated by 21.20% β -ionone). The 8% salt sample contained a mixture of alcohols and ketones, with β -ionone (10.38%) remaining the most abundant single volatile compound.	[20]
Rape stalks	China	12–20%	Soluble sugar content was lowest in the 12% salt samples (6.47 ± 0.29 mg/100 g), while fat content reached its highest value (4.55 ± 0.13 g/100 g) at the same concentration. Protein and total phenol content both demonstrated a nonlinear relationship, peaking in the 16% salt samples at levels comparable to those in fresh samples. In contrast, flavone content, initially highest in fresh samples (17.69 mg/g), declined with increasing salt concentration, with a significant reduction observed between 16% and 20% salt. Regarding flavor and taste, the concentration of free amino acids (FAAs), including both total and essential amino acids, generally decreased with higher salinity. However, the 12% salt samples contained the highest absolute levels of umami and bitter amino acids. Furthermore, sensory analysis based on taste active value (TAV) indicated that the umami impact was most pronounced in the 14% salt samples. Volatile analysis revealed that the relative percentage of esters—key flavor compounds—peaked at the 14% salt concentration before declining significantly at higher salt levels.	[21]
Kimchi	Korea	0.77–2.19% (w/w)	Kimchi with 0.77% salt exhibited a whiter coloration, supported higher LAB counts (4.11–9.26 log CFU/mL), and maintained a higher pH range (3.75–6.26) compared to samples with 1.53% and 2.19% salt. Although titratable acidity increased rapidly within the first 15 days and stabilized similarly across all groups, higher salinity (2.19%) appeared to delay the microbial succession toward LAB-dominated communities. High-throughput sequencing revealed distinct LAB distributions: the combined relative abundance of major LAB genera (Weissella, Leuconostoc, and Lactobacillus) totaled 61.1%, 75.5%, and 74.1% in kimchi with 0.77%, 1.53%, and 2.19% salt, respectively. Notably, the 2.19% salt group showed a higher proportion of Weissella but a lower proportion of Leuconostoc compared to the other salt concentrations.	[22]

Table 1. Cont.

Types of Fermented Foods	Region	Salt Concentration	Product Characteristic	Reference
Kimchi	Korea	0.77–2.19% (w/w)	Kimchi with 0.77% salt contained higher levels of putrescine, GABA, and xylose, while exhibiting lower concentrations of lactic acid, mannitol, glucose, valine, and phenylalanine.	[22]
Kimchi	Korea	1.4–2.5% (w/w)	<i>Lactobacillus gelidum</i> demonstrated a clear preference for lower salinity, with its highest relative abundance (43.69%) observed at a 1.4% salt concentration. In contrast, <i>Alkalibacterium funiforme</i> thrived under high-salt conditions, becoming the dominant microorganism at 2.5% salinity. This ecological shift was accompanied by a progressive decline in the proportion of <i>Leuconostoc</i> species as salt concentration increased from 1.4% to 2.5%. A significant inverse relationship was observed between salt concentration and acid production, with titratable acidity showing a marked decrease across the salinity gradient (1.4–2.5%). This pattern was particularly evident in lactic acid accumulation during the initial fermentation phase (the first two weeks), where substantially higher production occurred in low-salinity batches (1.4%) compared to their high-salinity counterparts (2.5%).	[23]
Table olives	Italy	6–8%	A lower salt level (6% NaCl), particularly when applied after an extended 30-day water fermentation (W30-MS), sustained significantly higher LAB viability throughout fermentation, while yeast populations remained largely unaffected by salinity variations. Physicochemical analyses revealed that although final brine pH converged across treatments, prolonged water fermentation before salting resulted in lower minimum pH values. Neither salt concentration nor fermentation duration significantly influenced residual oleuropein content. However, subtle modifications in phenolic profiles were observed, with 6% NaCl leading to decreased levels of specific phenolics. Volatile compound analysis demonstrated enhanced aroma complexity in 8% NaCl treatments, attributable to salt-induced partitioning effects. Sensory evaluation confirmed the expected saltiness enhancement in high-salt products, while delayed salt addition intensified sour and bitter notes, regardless of concentration. Notably, the W30-MS treatment developed distinctive fruity characteristics, likely mediated through sustained LAB activity and associated ester biosynthesis.	[24]
Chili paste	China	8–20%	Salt concentration exerted a differential impact on microbial ecology and quality attributes during chili paste fermentation. Elevated salinity enhanced bacterial diversity and richness, whereas fungal diversity peaked at 10–12% NaCl. Lower salt levels promoted rapid accumulation of total acidity, amino nitrogen, free amino acids, and organic acids; however, excessively reduced salinity favored the accumulation of biogenic amines (BAs). In contrast, higher	[25]

Table 1. Cont.

Types of Fermented Foods	Region	Salt Concentration	Product Characteristic	Reference
Chili paste	China	8–20%	salt concentrations (12–17%) were associated with greater diversity and abundance of volatile compounds, contributing to a more pronounced aroma profile. The application of multilayer sealed bags effectively prevented spoilage, highlighting their practicality and protective performance during fermentation. Overall, 12% NaCl provided the most favorable balance among microbial structure, flavor development, and sensory characteristics, representing an optimal condition for producing reduced-salt fermented chili paste with desirable quality and safety attributes.	[25]
Cucumber	Türkiye	2–8% (<i>w/v</i>)	Using a Box–Behnken design, this study investigated the effects of 2%, 5%, and 8% NaCl on naturally fermented cucumber pickles. The results showed that 5% NaCl was the optimal concentration, maintaining over 6 log CFU/mL LAB viability and achieving the highest total acid production, thereby balancing fermentation efficiency and product stability. In contrast, 2% NaCl had insufficient preservative effects, while 8% NaCl inhibited LAB metabolism.	[26]
Green olives	Tunisie	6–9% (<i>w/v</i>)	The optimal combination of 2% NaOH and 9% NaCl brine promoted the highest <i>Lactobacillus</i> growth (10^8 CFU/mL) and lactic acid production (0.726 g/100 mL brine). <i>Lactiplantibacillus plantarum</i> emerged as the predominant species across all treatments, while the combined lye pretreatment and lactic acid fermentation effectively eliminated coliform bacteria.	[27]
Table olives	Italy	6–8%	At 6% NaCl with extended water fermentation (30 d), LAB counts peaked, but microbial inhibition was weaker. This condition most significantly altered the nutritional and sensory traits of the olives, increasing specific phenolic compounds and “fruity” notes via <i>Lactobacillus</i> -derived esters. At 8% NaCl, richer volatile profiles were observed. Late salt addition (30 d) intensified “sour” and “bitter” tastes, irrespective of salt level, whereas early addition (15 d) with low salt yielded a distinct volatile profile. Final oleuropein content remained unaffected by salt concentration or fermentation duration and was partially retained in all treatments.	[24]
Green olives	Italy	4–8% (<i>w/v</i>)	At 4% NaCl, spoilage occurred in uninoculated controls but was prevented by <i>Lactocaseibacillus paracasei</i> IMPC2.1, which dominated from day 1. <i>Leuconostoc mesenteroides</i> prevailed later (76–95%), while <i>Enterobacteriaceae</i> persisted only in the control. At 8% NaCl, stability was achieved even without inoculation, alongside the highest bacterial diversity ($H = 0.85$). <i>Lactiplantibacillus pentosus</i> exhibited high strain diversity and persisted until 90 days, whereas <i>Lactocaseibacillus paracasei</i> IMPC2.1 showed slower initial growth. Elevated salinity accelerated the inhibition of enterococci and <i>Enterobacteriaceae</i> .	[28]

Table 1. Cont.

Types of Fermented Foods	Region	Salt Concentration	Product Characteristic	Reference
Table olives	Cyprus	7–10%	The combination of 7% salt and starter culture inoculation imparted novel organoleptic characteristics to the final product, as validated by sensory analysis. This demonstrates the feasibility of producing Cypriot table olives with a reduced salt content of 7%.	[29]
Table olives	Greece	8–10%	Under both 8% and 10% NaCl conditions, <i>L. pentosus</i> B281 and the co-culture of <i>L. pentosus</i> B281 and <i>L. plantarum</i> B282 exhibited the most rapid acidification, whereas <i>L. plantarum</i> B282 alone showed delayed pH reduction at 10% NaCl. <i>L. pentosus</i> B281 produced the highest lactic acid concentration (56 mM at 8% NaCl) and achieved strong colonization at the end of fermentation (81.2% at 8% NaCl; 93.3% at 10% NaCl), dominating in co-culture. Although <i>L. plantarum</i> B282 maintained high survival at 8% NaCl (83.3%), it failed to establish colonization at 10% NaCl, indicating lower salt tolerance.	[30]
Black olives	Greece	4–8% (<i>w/v</i>)	In 4% and 6% NaCl brines at 25 °C and 18 °C, LABs dominated, leading to a typical lactic acid fermentation characterized by high free acidity and low pH. In contrast, 8% NaCl inhibited LAB growth and promoted fermentative yeast activity, resulting in lower acidity and higher pH. The optimal fermentation conditions were 25 °C with 6% NaCl, achieving 142 mM (1.28% <i>w/v</i>) lactic acid and pH 3.8, which produced debittered, ready-to-eat olives after 5 months without off-odors. The identified LAB species included <i>Leuconostoc mesenteroides</i> , <i>Levilactobacillus brevis</i> , <i>Lactiplantibacillus plantarum</i> , and <i>Lactiplantibacillus pentosus</i> . The major organic acids detected were citric, malic, tartaric, succinic, lactic, and acetic acids.	[31]

2.2. Effects of Dry-Salting and Brine Fermentation Methods on Fermented Vegetables

Based on the method of salt application, fermented vegetables can be primarily classified into two distinct types: dry salting and brine fermentation. In the dry-salting process, salt is applied directly to the vegetable surface. Through osmotic action, moisture is progressively drawn out from the vegetables, ultimately forming a natural brine, which submerges them. In contrast, the brine fermentation process involves first dissolving salt in water to create a saline solution, which is then used to completely immerse the vegetables. These two methods establish fundamentally different biochemical environments, which in turn exert significantly different selective pressures on the aerobic, anaerobic, and halophilic microbial communities driving the fermentation process. This divergence in microbial dynamics ultimately leads to substantial differences in the final quality and characteristics of the fermented products.

Zhang et al. investigated the effects of dry salting versus brine fermentation on Yacai—a traditional pickled vegetable made from *Brassica juncea* Coss. var. *foliosa* Bailey, endemic to the Yibin region of China—and found that the dry-salting samples exhibited higher levels of total acid, amino acid nitrogen (AAN), and nitrite, supported greater microbial diversity throughout fermentation, and were more conducive to developing a high-quality reddish-brown color [32]. In some traditional fermentation systems, the concentration

used in brine fermentation can be higher than that used in dry salting, although this varies considerably depending on product type, regional processing practices, and fermentation objectives. This elevated salinity inhibits the growth of flavor-producing microorganisms and results in the generation of large volumes of high-salinity wastewater [33]. Zong et al., in the fermentation of Tongling white ginger, demonstrated that dry salting yielded the highest free amino acid content, while brine fermentation led in alcohols and aldehydes [34]. A comparative analysis on dry salting and brine fermentation of radish revealed significant differences in fermentation dynamics and product characteristics. Dry-salted radish required 30 days to mature (pH 4.7, TA 0.43 g/100 g, aw 0.90), exhibiting cumulative increases in reducing sugars (15.8 g/100 g), organic acids (1009.1 mg/100 g), and free amino acids (300.3 mg/100 g), with *Exiguobacterium*, *Glutamicibacter*, and *Leuconostoc* as dominant genera. In contrast, brine-fermented radish matured within 5 days (pH 3.4, TA 0.31 g/100 g, aw 0.96), characterized by lactic acid as the signature metabolite and *Lactobacillus* as the predominant genus, showing significant correlations with lactic acid, Arg, Val, and His [35].

Although dry salting of vegetables is often associated with more complex flavor development compared to brine fermentation products, the method inherently involves prolonged exposure of raw materials to open-air conditions during the initial salting stage. Because salt is applied directly to the vegetable surface without immediate full immersion in brine, moisture is gradually released and the formation of a protective saline environment is delayed. During this transitional period, fluctuations in ambient temperature, humidity, and oxygen availability can significantly influence microbial succession and metabolic activity. Consequently, the fermentation outcomes may be more sensitive to seasonal and environmental variations. Moreover, the absence of immediate anaerobic immersion during the early stages of the dry-salting process increases the likelihood of contamination by environmental microorganisms before LABs can establish ecological dominance. This risk primarily concerns the early fermentation stage rather than the fully matured product. If beneficial LABs fail to rapidly acidify the system, spoilage microorganisms or opportunistic pathogens may proliferate, potentially compromising product safety and raw material quality. In contrast, brine fermentation rapidly creates a relatively stable anaerobic and high-salinity environment, which can more effectively suppress undesirable microbial growth at the beginning of fermentation [36].

2.3. Influence of Other Components in Salt on Fermented Vegetables

Beyond NaCl concentration, the compositional profile of salt itself can significantly influence the quality of fermented vegetables. In a comparative study of four salt types—mineral salt, well salt, sea salt, and lake salt—Niu et al. reported that sea salt and well salt yielded superior fermented radishes, attributable to their distinct mineral composition and associated halophilic bacteria. Specific halophilic microorganisms, such as *Salinibacter*, *Desulfovermiculus*, *Aliifodinibius*, *Halovibrio*, and *Tepidimonas*, were found to influence fermentation dynamics by modulating key microbial communities including *Lactobacillus*, *Leuconostoc*, and *Vibrio*, thereby ultimately affecting product quality. Interestingly, these dominant halophilic microbes had a greater impact on fermentation outcomes than the chemical composition of the salt alone [37]. In a related study, Stoll et al. concluded that the use of iodized table salt does not adversely affect the fermentation process. Their work demonstrated that iodine diffuses effectively into cucumbers and remains stable during fermentation, reaching satisfactory concentrations in the final product. This finding is relevant because it indicates that the substitution of non-iodized salt with iodized salt does not compromise fermentation performance, thereby allowing fermented vegetable production to simultaneously support product quality and public iodine nutrition [38].

Furthermore, the type of salt used—such as one- or three-year-aged solar salt, dehydrated solar salt, or purified salt—has been shown to drive distinct microbial successions during kimchi fermentation, thereby shaping the resulting metabolite profile. While solar salts favored a microbial consortium dominated by *Leuconostoc* and *Weissella*, purified and dehydrated salts selected for *Lactobacillus sakei*. These shifts in the microbial ecosystem were directly correlated with significant variations in the concentrations of free sugars, organic acids, and amino acids, as explained by GC-MS analysis [39].

3. Challenges of Salt Reduction in Traditional Fermented Vegetables

The epiphytic microbiota of raw vegetables consists predominantly of aerobic bacteria such as *Pseudomonas*, *Enterobacteriaceae*, and *Corynebacterium*. Fermentation conditions—including high salinity, moderate temperature, and limited oxygen availability—create selective conditions that promote the dominance of LABs. However, because raw materials cannot be sterilized prior to processing, spoilage microorganisms often compete with LABs throughout both the initial and later stages of fermentation, increasing the risk of product deterioration [40]. Osmotic pressure induced by high salt levels normally suppresses the growth of spoilage-associated microbes. Reducing salt content diminishes this inhibitory effect, which can lead to several quality and safety issues in fermented vegetables, including proliferation of spoilage and pathogenic microorganisms, formation of hazardous compounds, development of off-flavors, and textural deterioration (Figure 4).

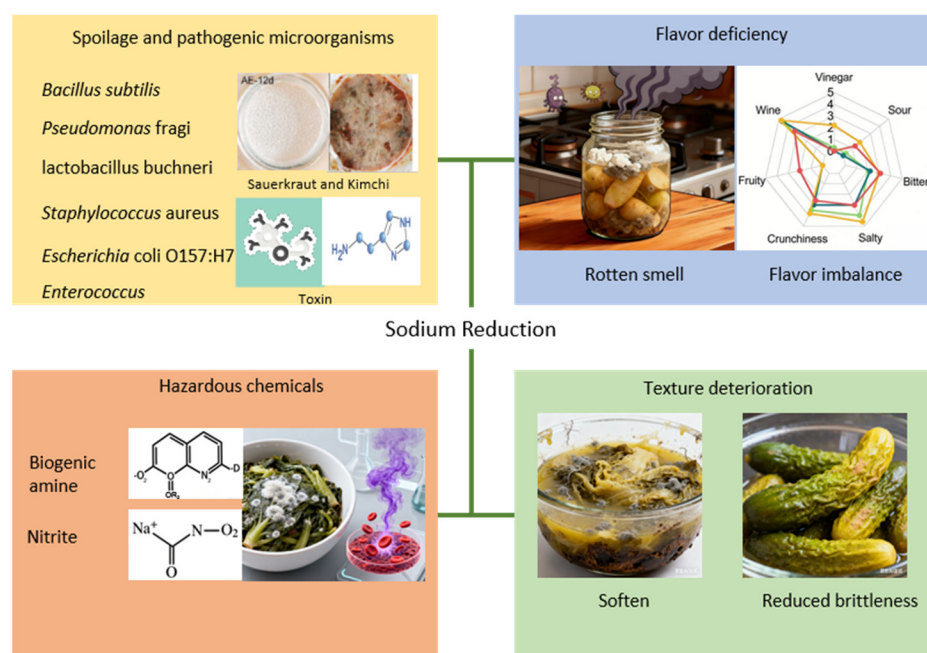


Figure 4. Effects of salt reduction on microbial safety, flavor formation, chemical hazards, and texture properties in fermented vegetables.

3.1. Spoilage and Pathogenic Microorganisms

3.1.1. Foodborne Disease Outbreaks Linked to Fermented Vegetables

Contamination by spoilage and pathogenic microorganisms continues to pose significant challenges in traditional vegetable fermentation (Table 2), primarily manifesting as foodborne disease outbreaks, the incidence of which varies according to regional, production, and food type factors.

Table 2. The main spoilage bacteria of fermented vegetables in foodborne disease outbreaks.

Samples	Country	Salt Concentration	Spoilage and Pathogenic Microorganisms	References
Kimchi	Korea	1.2–2.0%	<i>Escherichia coli</i> O99, <i>Escherichia coli</i> O120, <i>Escherichia coli</i> O169, <i>Escherichia coli</i> O6	[41]
Kimchi	Canada	-	<i>Escherichia coli</i> O157	[42]
Fermented vegetables	Cambodia	5–6%	<i>Enterococcus</i> spp., <i>Bacillus</i> spp., Coliforms, <i>E. coli</i>	[43]
Napa cabbage	Japan	-	Coliforms	[44]

Multiple outbreaks in the Republic of Korea have been associated with kimchi contaminated by foodborne pathogens. In 2012, *Escherichia coli* (*E. coli*) serotypes O99 and O120 were linked to 1193 cases of illness in Gyeonggi Province, while O169 infections caused 1642 cases the same year. Further outbreaks involving *E. coli* O6 were reported in 2013 and 2014. Studies indicate that pathogenic *E. coli* and *Salmonella* can survive for more than 12 days in kimchi at 4 °C, highlighting their persistence. Although the Korean government implemented mandatory HACCP management for kimchi processing in 2006 to enhance product safety, recurring outbreaks demonstrate that significant challenges in contamination control remain [41]. In January 2022, an outbreak of Shiga-toxin-producing *E. coli* (STEC) O157 linked to kimchi consumption was reported in Western Canada—the first such outbreak reported outside East Asia. Genomic surveillance identified 14 epidemiologically linked cases. Traceback investigations and product testing confirmed “Kimchi Brand A” from Manufacturer A as the source, with STEC O157 isolates from both open and sealed product samples genetically matching clinical strains. Epidemiological analysis indicated that 91% (10/11) of interviewed cases had consumed the implicated product, with contaminated napa cabbage hypothesized as the most likely vehicle [42]. A study evaluating microbial hazards in fermented vegetables from Cambodia analyzed 68 randomly purchased samples from wet markets in Phnom Penh using conventional culture methods. The results revealed widespread contamination: *Enterococcus* spp. showed the highest prevalence (34%), followed by *Bacillus* spp. (31%), coliforms (24%), and *E. coli* (10%). Notably, the opportunistic pathogen *Cronobacter sakazakii* was detected in one sample, while mixed vegetable products exhibited significantly higher coliform contamination rates (50%) compared to single-type preparations (13%) [43]. Following a major *E. coli* O157:H7 outbreak in Japan, an assessment of 500 commercial salted napa cabbage samples revealed high total coliform counts, indicating poor hygiene conditions. Bacterial loads peaked during summer months, with distribution temperature identified as the primary factor driving microbial growth [44]. Collectively, these findings indicate that coliforms and certain *E. coli* strains represent major contaminants in fermented vegetable products.

Throughout the journey from raw materials to consumption, fermented vegetables remain vulnerable to microbial contamination. As illustrated in Figure 5A, contamination may be endogenous (primary), originating from microorganisms inherent in the raw materials, or exogenous (secondary), introduced during production, processing, transportation, storage, sales, or consumption via external sources such as water, air, humans, animals, or equipment. Endogenous contamination represents the most critical stage, as all food materials naturally contain microorganisms—some harmless, others pathogenic—and market surveys frequently detect diverse bacterial types in food products [45,46].

Given the wide variety of fermented vegetables and their varying processing and storage conditions, spoilage is not uniform. A comprehensive understanding of these dynamics is essential for guiding production and preventing spoilage. Laboratory detection techniques and food microbiological risk assessment therefore serve as pivotal tools for

macro-level food safety management, providing critical insights and strategies to mitigate contamination risks, as outlined in Figure 5B.

The degree of microbial hazard in foods can be classified into three categories, as shown in Figure 5C: mild, moderate, and severe. The World Health Organization has identified *Salmonella*, *E. coli* O157:H7, *Listeria monocytogenes*, and *Staphylococcus aureus* as the four most critical foodborne pathogens. Consequently, many countries require testing for these organisms in imported and exported foods to safeguard public health [43]. Foodborne pathogens (FBPs) pose serious health risks, causing acute symptoms such as diarrhea, vomiting, fever, weight loss, abdominal pain, and other gastrointestinal manifestations, as well as chronic complications including renal, cardiac, and neurologic disorders (Figure 5D) [47].

In fermented vegetables, the combined effects of low pH, high salt concentration, and the antagonistic activity of LABs generally inhibit *Salmonella*, *Listeria monocytogenes*, and *Staphylococcus aureus*. In contrast, *E. coli* O157:H7 frequently emerges as the most common spoilage bacterium due to its acid tolerance [48]. However, multiple recent outbreaks linked to contaminated fermented vegetables indicate that this generalization may not always hold. Factors such as the adaptive capacity of spoilage bacteria and pathogens, and oxidative yeast activity that elevates brine pH, can trigger subsequent spoilage (Figure 5E) [49,50].

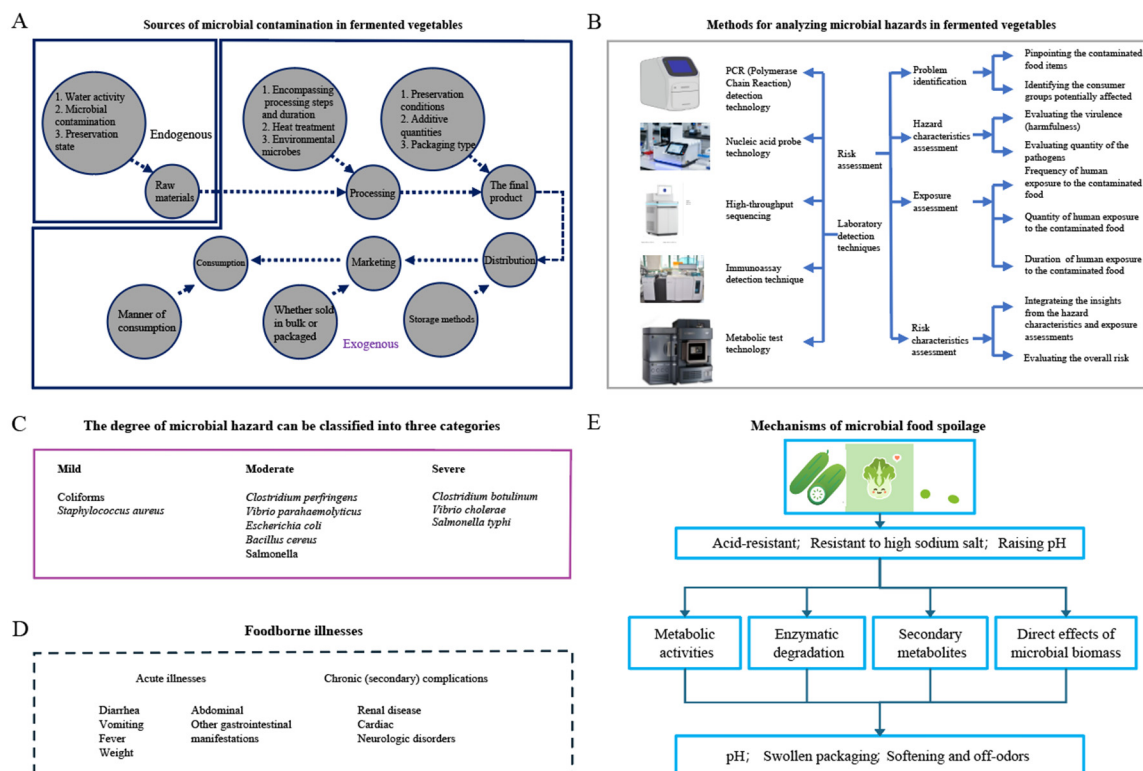


Figure 5. Integrated microbial safety and spoilage risk framework in fermented vegetables. Microbial safety in fermented vegetables is governed by a continuous chain of contamination risk, hazard detection, risk classification, and final quality and health outcomes. This figure illustrates the key stages of microbial risk formation and manifestation during production, storage, and consumption. (A) Sources of microbial contamination across the production and supply chain. (B) Analytical strategies for identifying and quantifying microbial hazards. (C) Risk-based classification of microbial hazards according to severity and potential health impact [46]. (D) Health risks associated with major foodborne pathogens relevant to fermented vegetable consumption [1]. (E) Microbial spoilage mechanisms which lead to sensory and structural deterioration of fermented vegetable products.

Given the multitude of factors and complex origins of microbial growth in fermented vegetables, it is essential to minimize contamination at every stage of production and distribution. Key strategies include managing contamination sources, interrupting transmission pathways, limiting favorable growth conditions, and implementing effective disinfection and sterilization protocols. The application of targeted microbial control technologies is crucial for ensuring the safety of fermented vegetable products. Through systematic analysis of kimchi production, five key measures have been identified for reducing coliform levels: (1) washing raw napa cabbage with sanitizer, (2) washing salted napa cabbage with sanitizer, (3) sanitizing subsidiary ingredients to reduce coliforms in kimchi seasoning, (4) maintaining clean food-contact surfaces, and (5) promoting rapid ripening [41].

3.1.2. Spoilage and Pathogenic Microorganisms in Reduced-Salt Fermented Vegetables

In vegetable fermentation, salt acts as a key preservative by reducing water activity, suppressing the growth of spoilage and pathogenic bacteria, and selectively promoting the proliferation of LABs, thereby ensuring successive fermentation and extending product shelf life [51,52]. Studies indicate that lowering salt levels increases microbial diversity; microbial abundance—including non-LAB species—may promote the accumulation of spoilage-related metabolites, such as BAs, posing food safety concerns (Table 3). Therefore, maintaining appropriate salt concentrations is crucial in effectively restricting the metabolism activity of spoilage microorganisms [52].

Xiong et al. examined the effects of salt concentration on spontaneously fermented sauerkraut and found that a 2% salt concentration accelerated maturation but failed to effectively suppress spoilage and pathogenic microorganisms. A 5% salt concentration promoted earlier reduction in fungi and *E. coli* while supporting a balanced fermentation profile; in contrast, 8% salt delayed maturation, impaired sucrose utilization, slowed LAB metabolism, and did not rapidly eliminate spoilage and pathogenic microbes [16]. Johanningsmeier et al. reported that *L. buchneri* utilizes lactic acid across a wide range of NaCl concentrations (0–6%), with the highest utilization rate at 2% NaCl and pH 3.8 in cucumber fermentation. This indicates that *L. buchneri* can initiate spoilage under varied fermentation conditions, potentially contributing to the formation of characteristic spoilage metabolites [53]. A comparative study on salt concentrations in vegetable fermentation found that low-salt conditions (1% NaCl, 1.1% CaCl₂) stimulated the growth of both *E. coli* and LABs. Medium-salt conditions (6% NaCl) reduced microbial growth overall, with *E. coli* being more strongly inhibited than LABs. Importantly, salt addition preferentially enhanced LAB growth over *E. coli*, thereby improving fermentation safety [48].

A crucial question in low-salt vegetable fermentation is whether the inhibitory effects of low pH and reduced salt act independently or synergistically. Johanningsmeier et al. investigated cucumbers fermented at pH 3.8, 4.3, and 5.0 under various NaCl concentrations (0%, 2%, 4%, and 6%). They observed anaerobic lactic acid degradation in all these conditions, regardless of salt level. Based on further analysis, they concluded that the pH threshold for preventing lactic acid utilization in reduced-NaCl fermented cucumbers is pH 3.2 or lower. Only cucumbers fermented with 6% NaCl to pH 3.2 completely prevented anaerobic lactic acid degradation by spoilage bacteria, indicating that the combined effect of salt concentration and pH is necessary to inhibit spoilage microorganisms [54].

Collectively, these findings indicate that bacterial contamination plays a major role in spoilage events reported in fermented vegetables. However, yeasts such as *Candida* spp., *Saccharomyces* spp., *Pichia* spp., *Issatchenkia* spp., and *Zygosaccharomyces* spp. are tolerant to high salt concentrations and can cause spoilage by producing an atypical aroma and turbid saline water, and degrading structural polysaccharides, leading to textural softening and overall product deterioration [4]. Several yeast species, including *Candida famata*, *Candida*

boidinii, *Saccharomyces cerevisiae*, *Pichia membranifaciens*, *Pichia anshurica*, and *Issatchenkia occidentalis*, have been implicated in the spoilage of table olives. At salt concentrations below 5–8%, these yeasts can proliferate and metabolize lactic acid, generating off-odors and gas, increasing brine pH, and thereby triggering uncontrolled spoilage cascades; similar mechanisms have been reported in pickled cabbage, particularly involving *Candida* spp. and *Pichia* spp. [55].

Table 3. The main spoilage bacteria and fungi in fermented vegetables.

Samples	Salt Concentration	Spoilage and Pathogenic Microorganisms	References
Cucumber	2% NaCl and pH 3.8	<i>L. buchneri</i>	[53]
Vegetable	1% NaCl, 1.1% CaCl ₂	<i>E. coli</i>	[48]
Cucumber	6%	<i>Pseudomonas</i>	[56]
Cucumber	2%	<i>Pseudomonas</i>	[57]
Olives	-	<i>Lactobacillus buchneri</i>	[58]
Olives	≤8%	<i>Staphylococcus</i> and <i>Enterococcus</i>	[58]
Olives	≤6%	<i>Candida famata</i>	[56]
Olives	≤5%	<i>Candida boidinii</i>	[59]
Olives	≤5%	<i>Saccharomyces</i>	[60]
Olives	≤5%	<i>Issatchenkia occidentalis</i>	[61]
Olives	-	<i>Pichia membranifaciens</i>	[62]
Cucumber	≤6%	<i>Pichia manshurica</i> and <i>Issatchenkia occidentalis</i>	[49]

3.2. Hazardous Compounds

Reducing salt levels in fermented vegetables not only increases the risk of contamination by spoilage and pathogenic bacteria but also promotes the accumulation of their harmful metabolites [2]. Even at low concentrations within established safety limits, these compounds present a growing health concern. BAs and nitrites are among the most common hazardous compounds that may accumulate in low-salt fermented vegetables.

3.2.1. Biogenic Amines

Biogenic amines (BAs) are nitrogenous organic compounds that are commonly present in fermented vegetables. Excessive intake of BAs is associated with various health problems, including headaches, dizziness, hypertension, nausea, vomiting, and increased cancer risk. In pickled products, BA formation is mainly associated with microorganisms possessing amino acid decarboxylase activity, including *Lactobacillus*, *Enterobacter*, *Pseudomonas*, and *Bacillus* species, and their accumulation is strongly influenced by processing conditions, with total BA levels in some fermented vegetables exceeding 1000 mg/kg [63,64]. A survey of fermented vegetables on the Polish retail market further revealed substantial variability, with total BA concentrations ranging from 30.29 ± 16.43 mg/kg in fermented olives to 612.1 ± 359.33 mg/kg in fermented Brussels sprouts [65]. Studies have demonstrated that lower concentrations correlate with increased BA accumulation. For instance, samples with 7% NaCl contained 161.41 mg/kg total BAs, significantly lower than the 31.53 mg/kg measured in 14% NaCl samples [66]. Similarly, in fermented radish paocai, histamine—one of the most hazardous BAs—was detected only in 1% salt brines at 6.85 mg/kg, while cadaverine levels in the 1%, 3%, and 5% samples were 1.50, 0.85, and 0.52 mg/kg, respectively. BA contents were consistently lower in higher-salt solutions by the end of fermentation [67].

Certain bacteria produce alkaline BAs as a survival mechanism in acidic environments. Therefore, low-salt fermented foods typically exhibit higher BA levels compared to traditional high-salt products, raising concerns regarding salt-reduced fermented vegetables. Although many countries have established BA limits for alcoholic beverages and

aquatic products, regulatory standards for fermented vegetables remain lacking. Current research focuses on elucidating the metabolic pathways of BA formation in salt-reduced fermented foods and developing effective control strategies. Promising approaches include the application of emerging technologies, the enhancement of functional microbial cultures, and bio-preservation methods [2]. Certain food-grade microorganisms, such as *Pediococcus acidilactici*, *Brevibacterium linens*, and *Lactiplantibacillus plantarum*, possess BA-degrading capabilities [68]. In addition, NaCl may inhibit the activity of BA-producing strains or gradually interfere with decarboxylase-associated cell membranes [69]. Traditional microbiological strategies for controlling BA production emphasize suppressing decarboxylase-positive microorganisms through rigorous hygienic practices, pasteurization, and the use of starter cultures lacking decarboxylase genes [70]. However, given the microbial diversity and metabolic complexity in low-salt fermented vegetable systems, more effective and tailored methods for BA mitigation require further development.

3.2.2. Nitrite

Nitrite, a recognized precursor of carcinogenic nitrosamines, serves as a key safety indicator in fermented foods. Previous studies have shown that both *E. coli* and certain marine fungi can produce nitrate reductase, which catalyzes the NAD(P)H-dependent reduction of nitrate (NO_3^-) to nitrite (NO_2^-). During fermentation, nitrite levels in pickled peppers with varying salt concentrations followed a similar trend—initially accumulating to a peak before declining. For instance, all samples reached their maximum nitrite content at 30 d of fermentation, with peak values of 1.40 mg/kg for 9% NaCl and 1.14 mg/kg for 24% NaCl samples [11]. In carrot fermentation, higher salt amounts (0%, 4%, and 8%) resulted in lower nitrite peaks (11.40, 9.13, and 8.93 mg/kg, respectively), and the timing of these peaks was delayed as salt levels increased [71]. Conversely, in fermented radish paocai, higher-salt brines (7% NaCl) exhibited greater nitrite peaks compared to lower-salt conditions, with the highest nitrite content recorded at 2.61 mg/kg [67]. The growth and nitrite degradation efficiency of microbial strains such as BNCC194165 decline with increasing NaCl concentration, with optimal activity observed between 0% and 6% NaCl. Concentrations exceeding 6% are likely to inhibit metabolic activity and reduce nitrite degradation capability [72].

Significant research has focused on mitigating nitrite risks in fermented vegetables. Strategies include screening of LABs with nitrite-reducing potential—such as *Lactobacillus brevis*, *Lactiplantibacillus plantarum*, and *Leuconostoc mesenteroides* isolated from kimchi [73,74]—optimizing fermentation parameters (e.g., maintaining pH below 4.5) [75], and employing auxiliary ingredients (e.g., salt, sugar, ginger, and garlic) to degrade existing nitrites [71]. In many fermented vegetables, nitrite levels remain below 2.0 mg/100 g (expressed as sodium nitrite), which meets the safety threshold established by the Chinese National Food Standard (GB2762-2022) [76] and is within the World Health Organization's Acceptable Daily Intake for healthy adults (0.06 mg/kg body weight per day, e.g., ~3.6 mg per day for a person weighing 60 kg) [77]. Nevertheless, given the potential for nitrite accumulation—particularly in salt-reduced products—further research is essential to evaluate and control nitrite formation in low-salt fermented vegetables.

3.3. Flavor Deficiency

Salt plays a critical role in shaping the flavor and sensory quality of fermented vegetables by regulating microbial growth and metabolism, thereby influencing the composition of key flavor compounds such as acids, aldehydes, alcohols, and esters [15,78]. In low-salt fermentation systems where microbial succession is not effectively controlled, flavor deficiency may emerge as a major quality concern. Pathogenic and spoilage microorganisms

can outcompete beneficial flora, generating off-flavors and disrupting the synthesis of desirable aromatic compounds. Furthermore, reduced salt levels directly alter the metabolic activity of flavor-producing microorganisms, leading to significant changes in the final flavor profile [2].

Studies across various fermented vegetables illustrate the impact of salt concentration on flavor development. In Northeast China, Liang et al. reported that high-salt (>6%) samples of suancai contained significantly higher levels of alcohols, aldehydes, phenols, ketones, sulfides, and heterocycles compared to low-salt (<6%) samples [14]. Xuecai—a traditional fermented vegetable product from Ningbo's Yinzhou district (Zhejiang Province) made from salted potherb mustard (*Brassica juncea* var. *multiceps*)—has been shown to exhibit elevated levels of total protein, total sugar, and amino acid nitrogen under salt brine conditions (7.6–17.6%), indicating enhanced microbial nutrient utilization during fermentation. This was associated with increased concentrations of total amino acids and organic acids, particularly umami-enhancing compounds such as glutamate and succinate, contributing to the characteristic umami intensity of the product [79]. In spontaneously fermented Northeast sauerkraut, volatile analysis revealed that 2.5% salt concentration yielded the most favorable sensory characteristics [78]. For ciba pepper, fermented at five salt concentrations (2%, 4%, 6%, 8%, and 10%), electronic nose analysis indicated that higher salt levels (6%, 8%, and 10%) promoted the production of volatile flavor compounds, including aromatic compounds and propanol, compared to the lower-salt treatments (2% and 4%). This may be attributed to excessive acid production and altered microbial dynamics under low-salt conditions [10]. Zhang et al. investigated pickled *Brassica napus* at different salt concentrations (4–8%) and found that 6% salt resulted in the highest total free amino acid (FAA) content, particularly in Asp, Glu, Gln, and Pro, along with the most prominent sweetness. In radish fermentation, sweet-tasting FAAs (Thr, Ser, Gly) increased with salt concentration, with the highest Ala level detected at 7% salt. Isothiocyanates, key flavor compounds in pickled summer radish, peaked at 5% salt, followed by 3% and 7%, with the lowest levels observed at 1% salt [67].

Overall, flavor defects in low-salt fermented vegetables originate primarily from microbial metabolic shifts: increased spoilage microbiota generate off-flavors and inhibit beneficial aroma-forming microorganisms while simultaneously suppressing metabolic pathways essential for characteristic flavor development [2]. To fundamentally compensate for flavor loss in low-salt fermented foods, a deeper understanding of the interactions among volatile compounds, microbial diversity, and the metabolic network is essential. The divergent observations reported for low-salt fermentation are largely attributable to differences in microbial succession patterns. Reduced salinity may promote LAB activity and metabolite production when a stable microbial structure is rapidly established. However, lower salt levels also decrease selective pressure within the fermentation system. In cases where LABs do not achieve early dominance, spoilage-associated microorganisms may proliferate, leading to altered metabolic profiles and the formation of undesirable flavor compounds. Thus, the influence of salt reduction on flavor development depends on the dynamics of microbial competition, the rate of acidification, and the overall level of process control.

3.4. Texture Deterioration

Salt significantly influences the textural properties of fermented vegetables—such as their hardness, brittleness, and chewiness—by modulating microbial metabolism and enzyme activity during processing. Salt plays a dual role in vegetable fermentation. It generates osmotic pressure, which facilitates the release of intracellular soluble compounds such as sugars that serve as nutrients for fermenting microbiota. An optimal salt con-

centration is therefore crucial, as low salinity can lead to texture softening. Conversely, high salinity strongly inhibits both undesirable and beneficial microorganisms, which may slow metabolic activity and delay fermentation. Although elevated salt concentrations can enhance microbial stability, they also increase the sodium content of the final product, potentially conflicting with dietary recommendations for reduced salt intake. A quantitative study on pickled peppers demonstrated this concentration-dependent effect, showing that a moderate salt level (4.51%) achieved superior firmness (47.00 ± 5.94 N), elasticity (0.41 ± 0.01 cm), and chewiness (4.44 ± 1.24 mJ) compared to lower (2.94%) or higher (8.04%) salt concentrations; although 8.04% salt produced comparable chewiness (4.57 ± 0.85 mJ), it resulted in reduced firmness and elasticity, indicating that moderate salt levels provide an optimal balance between microbial stability, textural quality, and health considerations [11]. In olives, Sacchi et al. observed that varying salt concentrations (6% and 8% NaCl) influenced sensory attributes, with the 6% treatment yielding slightly lower values compared to the 8% treatment [24]. Similarly, Xiong et al. reported that salt concentration significantly influenced the sensory characteristics of ciba pepper, with notable differences ($p < 0.05$) in color, odor, texture, and taste across all tested levels. Samples with medium-to-high salt concentrations—6% for odor and taste, and 8 and 10% for texture—received the highest sensory scores; meanwhile, the 2% samples consistently scored lowest, indicating a clear impact of salt level on overall sensory quality [10]. Low-salt pickles (10–30 g/kg) are generally softer than their high-salt counterparts (~100 g/kg), as salt reduction compromises crispness and structural integrity. A study on Chinese paocai further demonstrated that decreasing salt content not only reduced textural crispness but also increased susceptibility to spoilage microorganisms during long-term storage, highlighting the dual impact of salt reduction on both quality and microbial stability [80].

For fermented vegetables, crispness is a key textural attribute intrinsically linked to the pectin content within vegetable tissues. Under low-salt conditions, pectin becomes more susceptible to hydrolysis into soluble pectic acid due to enhanced activities of pectinase and cellulase, leading to tissue softening and a loss of crispness. Salt concentration significantly influences the overall sensory profile of the final product. Medium-to-high salt samples generally receive superior sensory scores, largely because salt helps mitigate the loss of intercellular components and suppress the activity of cell wall-degrading enzymes such as pectinase. This inhibition slows the decomposition of pectic substances, thereby preserving the structural integrity of vegetable cells.

Various strategies have been explored to develop low-salt fermented foods, including gradual salt reduction, the structural modification of salts, and the partial substitution of NaCl with other chloride salts. However, reducing salt content often compromises the sensory acceptability of the final product. This is primarily attributable to the multifaceted role of salt in flavor perception, such as enhancing salty taste, facilitating the release of volatile compounds, suppressing bitterness, and modulating the microbial community structure [81].

4. Sodium-Reduction Strategies in Fermented Vegetables

Current alternative approaches for reducing salt content in fermented vegetables can be broadly classified into the following categories: (1) substitution of NaCl with other chloride salts; (2) biological strategies for salt reduction; and (3) fermentation-process-based strategies (Figure 6).

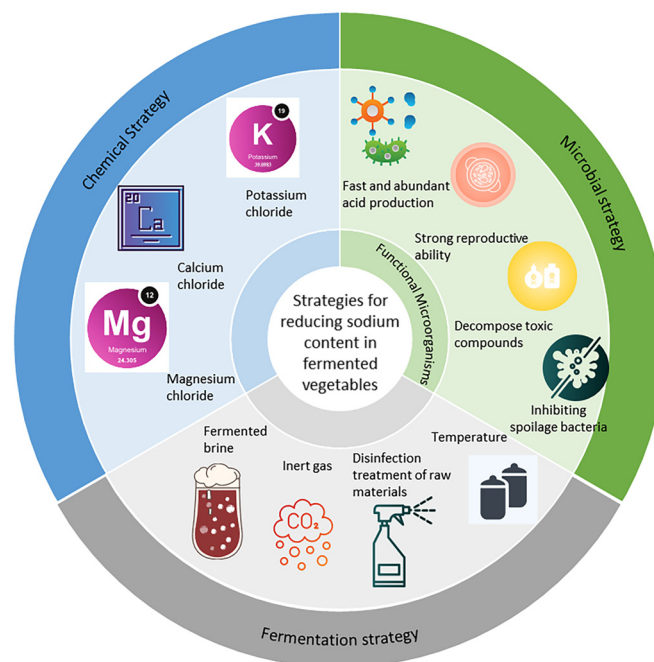


Figure 6. Strategies for salt reduction in producing fermented vegetables.

4.1. Physical Strategies

Saltiness perception is primarily determined by salt dissolution and diffusion kinetics, with faster rates enhancing perceived intensity [82]. These kinetic parameters are influenced by the physical properties of salt crystals including size, shape, density, and surface area. Novel salt forms engineered to optimize these structural properties for enhanced saltiness perception in solid foods have been developed; however, their application is often limited by high production costs. Furthermore, the effects of such modified salts on critical quality attributes of traditional fermented products—including safety, texture, sensory characteristics, and microbial ecology—require further comprehensive evaluation. Although advanced technologies—such as high-pressure processing, ultrasound, microwave, and vacuum impregnation—have been increasingly applied in recent decades to develop low-salt fermented foods (e.g., meat products, sufu, and fermented milk) while preserving product quality, the application of structurally engineered salt forms in fermented vegetable systems remains largely unexplored [2].

4.2. Chemical Strategies

The partial substitution of NaCl with alternatives like KCl, CaCl_2 , and MgCl_2 in fermented vegetables effectively reduces salt content while preserving saltiness. This approach aligns with low-salt, high-potassium/calcium dietary recommendations, which support cardiovascular health and may lower risks of osteoporosis and colon cancer. Moreover, the minerals involved (K, Ca) are approved for food fortification in Europe.

4.2.1. Substitution of NaCl with KCl

Experts and scientists in the food industry are actively pursuing strategies to lower salt intake while maintaining the flavor, texture, and nutrition quality of food products [83]. Among the current salt-reduction approaches, potassium chloride (KCl) is regarded as an ideal substitute because it imparts a certain salty taste, promotes salt excretion, helps lower blood pressure, and may reduce the risk of stroke, coronary heart disease, and other cardiovascular conditions. Increased potassium intake is also positively correlated with slowing age-related bone degradation and reducing the risk of kidney stone development.

Although the WHO recommends that adults consume at least 3.5 g of potassium daily, global progress towards this target remains slow [84].

Several studies have developed various low-salt fermented vegetables using KCl as a partial NaCl replacer, evaluating their properties. In a work on low-salt edible olives by Sivigliano and Castelvetro, NaCl was partially replaced with KCl at 25%, 50%, and 75% of the total salt content, while maintaining overall salt levels between 7% and 9%. The results showed that partial KCl substitution (25%, 50%, and 75% of the total salt content) did not increase contamination risk or promote overgrowth of pathogenic or spoilage microorganisms [85]. In a study on low-salt radish kimchi by Li et al., the researchers replaced 30% of the salt content with KCl, and found that this significantly increased the levels of mannitol and glutamic acid, enhancing desirable fresh, sweet, and umami tastes [86]. Another study on low-salt pickled Chinese cabbage found that KCl substitution (0–100% replacement) stimulated LAB growth and lactic acid production; however, consumer preference was lowest at full replacement. The authors concluded that up to 50% KCl substitution optimally reduces salt without compromising acceptability [87].

To date, no safety issues have been reported in fermented vegetables produced through partial salt substitution. Nevertheless, the broader effects and potential side effects of salt replacement in fermented vegetables remain insufficiently studied. Existing studies indicate that salt substitutes may introduce sensory abnormalities and undesirable bitter or metallic flavors [83]. Thus, high-level replacement of NaCl with KCl remains challenging, largely due to the risk of compromising sensory quality, despite the demonstrated health benefits of KCl.

4.2.2. Substitution of NaCl with CaCl_2

In a study on low-salt cucumbers by McFeeters and Pérez-Díaz, replacing 100% of salt with CaCl_2 resulted in a primary metabolic pathway in which cucumber sugars were predominantly converted into lactic acid, driving the pH below 3.5. This fermentation pattern matched that observed with salt as the primary brining agent. During storage, both lactic acid concentration and pH remained stable, and no detectable production of propionic or butyric acid was observed, indicating the absence of spoilage microorganisms [88]. The efficacy of different metal salts in replacing NaCl varies with raw materials and requires experimental validation. For instance, López-López et al. observed that olives fermented with partial substitution of NaCl by CaCl_2 developed a bitter taste, which could lead to consumer rejection [89].

4.2.3. Substitution of NaCl with Binary Salt Mixtures

In a study on low-salt olives, Panagou et al. replaced 50–66% of salt with KCl and CaCl_2 while maintaining a total salt concentration of 8%; the results showed that a 50% substitution with KCl (4% NaCl and 4% KCl) yielded a final product of acceptable quality and favorable sensory properties, including low bitterness scores in the sensory analysis [90]. In the study of Constandache et al. on low-salt pickled apples, substituting salt with KCl and MgCl_2 led to a rapid increase in LABs and a significant pH decrease during fermentation, with only minor impacts on product characteristics, confirming its feasibility as a sodium-reduction strategy [91].

4.2.4. Substitution of Sodium Chloride with Non-Salt Compounds

In a study on low-sodium white cabbage by Pires-Cabral et al., substituting 53–66% of salt with the halophyte *Salicornia ramosissima* enhanced the antioxidant activity of the final product [92]. In the study of Huang et al. on low-salt Yunnan suancai, substituting 30–50% of salt with KCl and κ -carrageenan showed that the 30% replacement formula best preserved the texture and acceptability of the product [93]. Sichuan paocai—a tra-

ditional Chinese fermented vegetable produced by soaking vegetables in a 6–8% salt solution with spices under anaerobic conditions, primarily driven by lactic acid bacteria (LABs)—was shown to benefit from the addition of prickly ash extract and hydroxypropyl- β -cyclodextrin at 4% of the salt content in the study of Zhang et al.; these additions inhibited Enterobacteriaceae while promoting LABs, reduced the nitrite peak by 3 mg/kg, shortened maturation time, and suppressed spoilage fungi including *Geotrichum*, *Cladosporium*, and *Candida* [94].

4.3. Biological Strategies

Conventional vegetable fermentation relies on high salt concentrations to regulate microbial activity and fermentation kinetics, which can often lead to issues such as insufficient acidity production, loss of umami substances, and increased processing costs. Recent studies indicate that the core driving force of paocai fermentation is the autochthonous LAB communities (e.g., *Weissella*, *Leuconostoc*, and *Lactobacillus*) present on the raw materials, whose natural succession dynamics govern flavor formation. However, high-salt environments can inhibit the activity of these core microbial groups while promoting the proliferation of salt-tolerant bacteria, thereby adversely impacting flavor formation. Accordingly, a novel salt-reduced strategy has been proposed: by precisely controlling fermentation conditions—such as moderately reducing salt concentration and controlling temperature—the inherent core LABs or inoculated starter cultures can be selectively promoted to rapidly colonize and establish dominance during the initial fermentation stage. This approach enables a safe, stable, and controllable fermentation process under low-salt conditions. The strategy aims to reduce the final salt content of the product while better preserving beneficial components such as umami amino acids and microbial metabolites, ultimately yielding fermented vegetables with a milder flavor profile, enhanced quality and safety, and reduced product costs.

4.3.1. Salt-Reduction Strategy Using Functional Microorganisms

Functional microorganisms are defined as microbes that actively contribute to the safety, quality, nutrition, and health benefits of fermented foods. Numerous studies indicate that LABs serve as the primary functional microorganisms in vegetable fermentation. Employing either single strains that produce beneficial metabolites or mixed strains with compatible growth kinetics and complementary metabolic profiles can significantly enhance the safety and quality of low-salt fermented products [2]. As shown in Figure 7, LABs inhibit spoilage and pathogenic microorganisms through the secretion of antimicrobial compounds. The functional microorganisms and their key metabolic characteristics in representative low-salt fermented vegetables are summarized in Table 4.

In low-salt paocai, challenges such as microbial spoilage and accumulation of BAs and nitrites can be effectively addressed by using defined starter cultures (e.g., *Lactiplantibacillus plantarum*, *Leuconostoc mesenteroides*, and *Lactiplantibacillus pentosus*). These starters accelerate dominance of beneficial bacteria, shorten fermentation time, enhance free amino acid content and flavor complexity, reduce hazardous compounds, and improve sensory scores compared to spontaneous fermentation [95].

LABs produce a large variety of antimicrobial substances—including organic acids (lactic and acetic acid), ammonia, bacteriocins, ethanol, reuterin, hydrogen peroxide, and diacetyl—which inhibit foodborne pathogens and spoilage organisms, thereby enhancing food safety [96]. Additionally, these metabolites significantly influence the final flavor and texture of the product.

Tzamourani et al. investigated low-salt black olive fermentation by substituting 50% of NaCl with KCl. The process was initiated by inoculation with *Lactiplantibacillus pentosus* B363 and *Lactiplantibacillus plantarum* B380. This strategy resulted in rapid LAB proliferation and accelerated acid production, with no detectable *Enterobacteriaceae* by the end of fermentation. These findings confirm the feasibility of producing low-salt natural black olives that retain typical fermentation characteristics and offer potential probiotic benefits [97]. Similarly, in sauerkraut fermentation, Zubaidah et al. reduced NaCl concentration by 10–50% and simultaneously inoculated the system with *Lactobacillus casei* as a starter culture. This combined strategy significantly enhanced LAB counts (increasing from 1.38×10^9 to 3.86×10^9 CFU/mL) and improved fermentation efficiency and antioxidant capacity, with optimal results achieved at only 2% salt content [98]. Johanningsmeier et al. further showed in cabbage fermentation that inoculation with *Leuconostoc mesenteroides* resulted in rapid fermentation initiation, producing sauerkraut with firmer texture, reduced off-flavors, and a more uniform pH decline, ensuring consistent product quality [99]. In work on “Almagro” eggplants, Ballesteros et al. found that using *Lactiplantibacillus plantarum* in brines with $\leq 6\%$ NaCl shortened fermentation time through rapid sugar consumption and acid production, yielding products of acceptable quality despite a slight bitterness potentially associated with the specific starter culture [100]. For fermented peppers, Mani-López et al. observed that inoculation with *Latilactobacillus sakei* reduced fermentation time by 57% compared to spontaneous fermentation and established stable pH, retrievable acidity, color, aroma, and texture with only 2% NaCl, ultimately enhancing the sensory characteristics of the final product [101]. In another olive study, Tataridou et al. demonstrated that the addition of *Lactiplantibacillus plantarum* (with 2.5% NaCl) improved sensory and nutritional characteristics via antagonistic activity against pathogens and oleuropein degradation [102]. Finally, in Northeast Chinese sauerkraut, He et al. showed that *Lactobacillus curvatus* LC-20 became dominant under low-salt conditions (0–1% NaCl), promoting organic acid and nitrite reductase production, which accelerated nitrite degradation and yielded the highest sensory score at 1% salt concentration [103].

Among functional microorganisms, *Lactiplantibacillus plantarum* is one of the most significant and widely applied species in the agri-food sector. It is utilized to safeguard plant health, improve food texture, aroma, and flavor, serve as a probiotic, and act as a biopesticide. It has also emerged as a key microbial starter for salt-reduction applications [104]. Its prevalence is attributed to a combination of robust technological and probiotic potential [105].

Research further indicates that LABs, yeasts, and *Enterobacteriaceae* all participate in the metabolic degradation of BAs and nitrites during vegetable fermentation. The acidic microenvironment of the fermentation system also influences the transformation of nitrogenous compounds. Therefore, the application of autochthonous LABs capable of degrading BAs or nitrites represents another viable biological strategy for salt reduction in fermented vegetables [4].

In summary, functional microbial enhancement holds significant potential for mitigating the adverse effects of salt reduction. It not only improves the safety of low-salt fermented foods but can also impart unique flavors, nutritional components, and antimicrobial properties. The beneficial effects are not merely additive; complex interactions between microbial strains and with the fermentation environment critically influence the final product quality [4].

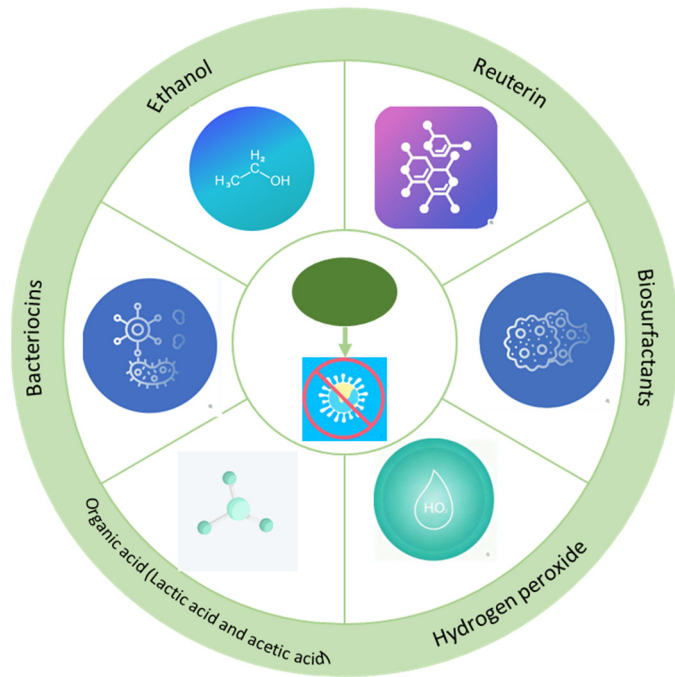


Figure 7. Some of the antimicrobial substances excreted from LABs [96,106].

Table 4. Functional microbial enhancement in representative low-salt fermented vegetables.

Fermented Vegetable	Functional Microorganism	Reduction in Salt Content	Product Characteristic	Reference
Black olives	<i>Lactiplantibacillus pentosus</i> B363 and <i>Lactiplantibacillus plantarum</i> B380	50%	<i>L. pentosus</i> and <i>L. plantarum</i> exhibited high recovery rates (80–89%), dominated the microbiota, and drove a typical lactic acid fermentation. The salt reduction was sensorially transparent, producing safe and acceptable olives.	[97]
Sauerkraut	<i>Lactobacillus casei</i>	10–50%	It improved the fermentation efficiency and antioxidant capacity of kimchi, thereby achieving the optimal effect at just 2% salt.	[98]
Cabbage	<i>Leuconostoc mesenteroides</i>	50%	<i>L. mesenteroides</i> addition to cabbage fermentations ensured that texture and flavor quality were retained while allowing 50% NaCl reduction.	[99]
Pepper	<i>Latilactobacillus sakei</i>	-	By enabling rapid development of physicochemical and sensory attributes, <i>Latilactobacillus sakei</i> cut fermentation time by 57% and lowered the NaCl requirement for pepper fermentation, thereby achieving a high-quality product with enhanced sensory characteristics in a shorter time.	[101]
Table olives	<i>Lactiplantibacillus plantarum</i>	42.5%	There were inhibitory and antagonistic effects against spoilage and pathogenic bacteria.	[102]
Sauerkraut	<i>Lactobacillus curvatus</i> LC-20	90%	Based on optimal microbial growth, acidification, and superior sensory scores at 1% salt, <i>L. curvatus</i> demonstrates high potential as a starter culture for producing low-salt suancai without compromising quality.	[103]

4.3.2. Salt-Reduction Strategy Using Fermented Brine

Fermentation brine, typically regarded as a byproduct of vegetable fermentation, can be repurposed as a natural starter culture. Studies indicate that brine-based starters often yield higher-quality pickles compared to those produced with artificially isolated LABs, highlighting their value in sustainable food production [79]. In low-salt paocai, Zhao et al. demonstrated that the use of fermented brine—containing dominant microorganisms and organic acids—reduced the formation of nitrite and BAs. When applied in a 4% NaCl fermentation, the brine promoted the growth of LABs and yeast, accelerated the consumption of reducing sugars, inhibited undesirable enterobacteria, and resulted in low levels of nitrite and biogenic amine, thereby supporting the production of safer, low-salt fermented vegetables [4].

4.3.3. Salt-Reduction Strategy Using No-Sodium Salt

In a sodium-free Sichuan paocai study by Lai et al., boiling raw materials, inoculating starter cultures, and employing low-temperature fermentation collectively enabled salt-free fermentation. This approach effectively eliminated surface-associated microorganisms, suppressed spoilage bacteria, and accelerated acid production, demonstrating that reducing native microbiota while promoting the dominance of beneficial strains is an effective strategy for sodium reduction [107].

4.3.4. Salt-Reduction Strategy Using Inert Gas

Recent studies indicate that initial packaging conditions (gas composition or liquid medium) significantly influence microbial succession, enzyme activity, and quality in fresh-cut, pickled, and fermented vegetables. For instance, in kimchi, gas flushing promotes yeast growth, whereas vacuum packaging favors the retention of LABs. Similarly, in fermented cucumbers and paocai, vacuum packaging effectively suppresses microbial proliferation, inhibits pectinase-mediated degradation, redirects microbial metabolism to reduce gas production, and consequently maintains textural stability while preventing package bloating. These findings collectively demonstrate that controlled packaging atmospheres provide a practical strategy to improve the storage stability and quality of low-salt fermented vegetables [108]. In the study of Zhang et al. on low-salt Zhejiang pickle, CO₂-modified-atmosphere packaging effectively suppressed biogenic amine accumulation by reshaping microbial community and inhibiting amine-forming enzymes, reducing total BAs from 63.66–161.41 mg/kg to 1.88–24.76 mg/kg and enabling production with only 7% salt [109]. Anaerobic fermentation under an exogenous CO₂-induced modified atmosphere thus serves as an effective method for regulating microbial communities in fermented foods, enhancing *Lactobacillus*-associated populations while inhibiting spoilage bacteria, and simultaneously improving the product quality by optimizing color and crispness, and reducing nitrite content [66].

4.3.5. Salt-Reduction Strategy Using Synergistic Control of Fermentation Temperature and Salt Concentration

Fermentation temperature plays a critical role in shaping fermentation kinetics, microbial diversity, biomass, and the formation of key flavor compounds. For example, Northeast Chinese sauerkraut is typically fermented at low-to-medium temperatures (5–15 °C), while Sichuan paocai is fermented at medium-to-high temperatures (15–30 °C) [110]. In a study on Northeastern sauerkraut by Liu et al., the combination of 15 °C fermentation temperature and 1.5% NaCl concentration modulated the microbial composition, thereby regulating physicochemical properties, quality, and safety. This treatment resulted in the lowest biogenic amine content (40.97 mg/kg), the highest total volatile compounds (493.00 µg/kg), and favorable color and texture characteristics [111].

5. Further Perspectives

Reducing salt content in fermented vegetable is not a matter of simply omitting salt, given its multifaceted role in governing physicochemical properties, textural characteristics, and food safety. This review has summarized the salt-reduction strategies currently employed in fermented vegetable processing, with emphasis on salt substitutes and biological salt-reduction strategies.

Growing awareness of the potential risks associated with high-salt diets positions low-salt fermented vegetables as a promising direction for the industry. By applying the strategies outlined herein, a 20–50% salt reduction can be achieved in traditional fermented vegetables, typically without compromising safety or quality.

Our observations for microbial functions and environmental control in salt reduction for fermented vegetables are detailed here:

(1) Harnessing microbial functions.

The critical role of microorganisms and their metabolites is paramount in compensating for the quality deficits resulting from salt reduction. Therefore, in-depth research into microbial functionality is essential. Promising strategies include the screening and application of robust strains characterized by rapid proliferation, high acid production, and abundant bacteriocin synthesis, as well as the adoption of multi-strain starter cultures. During fermentation, microorganisms naturally enhance product safety by producing a spectrum of antimicrobial compounds such as organic acids, alcohols, carbon dioxide, and bacteriocins. LABs, typically the dominant microbiota in fermented vegetables, convert carbohydrates into lactic acid, thereby acidifying the environment. Concurrently, yeasts contribute by generating ethanol and CO₂, which collectively foster an anaerobic and antimicrobial milieu. This synergistic activity establishes a natural barrier against pathogens and spoilage microbes through competitive exclusion [86].

(2) Optimizing the fermentation environment: Precise control of the fermentation conditions offers a practical avenue for facilitating salt reduction.

- Temperature:

As a key parameter governing microbial growth and enzymatic activity, temperature control provides a straightforward and effective means of steering fermentation. Regulating temperature can accelerate the process and represents one of the most efficient strategies for minimizing BA formation. While the effects of constant temperatures have been well studied, research on the effects of dynamic temperature profiles on fermentation kinetics and final product quality remains relatively limited.

- Atmosphere and oxygen:

The composition of the gaseous environment significantly influences microbial dynamics. Introducing gases such as CO₂ or N₂ at the initial stage can selectively inhibit foodborne pathogens, promote rapid LAB proliferation, and thus support salt reduction. Moreover, oxygen content critically determines the population of spoilage bacteria, especially during early fermentation. Strategies that rapidly establish an anaerobic environment are crucial, as they favor LAB dominance, limit contamination by undesirable microbes, and provide a robust foundation for low-salt fermentation.

- Brine and nutrients:

Fermentation brine is not merely a salt solution but a complex ecosystem containing dominant microbial strains and their metabolites, making it a valuable target for research aimed at optimizing low-salt processes. Additionally, the strategic supplementation of specific nutrients can direct microbial metabolism away from

undesirable compound formation, further supporting the production of safe, low-salt products.

(3) Synergistic application of combined strategies.

A single approach is often insufficient to address the multifaceted challenges of salt reduction. Integrating multiple strategies holds greater promise. For instance, combining chemical strategies—such as using alcohol-based antimicrobials to suppress spoilage and pathogenic bacteria—with biological enhancements, like reinforcing functional microbial cohorts, can yield synergistic effects. Such integrated approaches leverage the respective advantages of each strategy and possess considerable potential for developing high-quality, low-salt fermented foods.

6. Conclusions

In summary, salt plays an indispensable role in determining the quality, texture, and safety of fermented vegetables. A variety of feasible salt-reduction strategies have been developed and applied in fermented vegetable processing, comprising mainly salt substitutes and biological salt-reduction strategies. By combining microbial function regulation, fermentation environment optimization, and multi-technology synergies, it is possible to reduce salt content by 20–50% while maintaining product safety and quality. These strategies provide practical and effective technical support for the development of healthier low-salt fermented vegetable products and promote the sustainable and innovative development of the fermented vegetable industry.

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