Effects of Lactic Acid Bacteria Replacement Sodium Dehydroacetate on Food Safety and Functionality of Fruits and Vegetables

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Abstract: This study investigates the feasibility of lactic acid bacteria as a sustainable alternative to sodium dehydroacetate (DHA-S) in fruit and vegetable preservation, conducting a systematic evaluation across three dimensions: safety, functionality, and cost-effectiveness. Comparative analysis reveals that lactic acid bacteria achieve comparable preservative efficacy to DHA-S through multi-target antibacterial mechanisms and metabolic regulation, while enhancing sensory quality and nutritional value. Their natural attributes better align with clean label trends. Safety assessments demonstrate that lactic acid bacteria pose no chemical residue risks and exhibit potential probiotic benefits, showing significantly higher consumer acceptance than chemical preservatives. Although challenges remain in large-scale implementation regarding strain adaptation and cost optimization, technological advancements and improved standards position lactic acid bacteria as a promising sustainable replacement for DHA-S, driving the green transformation of fruit and vegetable preservation.

Keywords: Lactic Acid Bacteria; Sodium Dehydroacetate; Fruit and Vegetable Preservation; Biological Preservative; Clean Label

1. Introduction

With growing consumer concerns about food additive safety, traditional chemical preservatives like sodium dehydroacetate are facing increasing challenges. While effective in inhibiting microbial growth, their potential health risks have driven researchers to seek safer natural alternatives. Lactic acid bacteria, recognized as a safe microorganism, not only exhibit excellent antimicrobial properties but also enhance food functionality through metabolic byproducts, offering innovative solutions for fruit and vegetable preservation. This study systematically investigates the feasibility of using lactic acid bacteria as sodium dehydroacetate substitutes, analyzes their mechanisms in ensuring food safety and improving functional properties, and provides theoretical foundations for developing novel biological preservation technologies. The research holds significant importance for advancing the food industry's transition toward green and sustainable development.

2. Application and Limitation of Sodium Dehydroacetate in Fruit and Vegetable Preservation

2.1 Chemical Properties and Bacteriostatic Mechanism of Sodium Dehydroacetate

Sodium dehydroacetate, a broad-spectrum chemical preservative with the chemical name 3-acetyl-6-methyl-2,4-pyranodione sodium salt ($C_8H_7NaO_4$), exhibits high water solubility and thermal stability. The α and β-unsaturated carbonyl groups in its molecular structure confer strong electrophilic properties, enabling it to react with reactive groups such as thiols (-SH) and amino groups ($-NH_2$) within microbial cells, thereby disrupting the normal functions of proteins and enzymes. In acidic to neutral environments, sodium dehydroacetate effectively dissociates into dehydroacetic acid (DHA), further enhancing its bacteriostatic activity. Its antibacterial mechanisms primarily include: (1) disrupting microbial cell membrane permeability to cause intracellular substance leakage; (2) inhibiting key metabolic enzymes to impede energy metabolism; (3) interfering with DNA replication and transcription to suppress microbial proliferation [1].

Sodium dehydroacetate exhibits significant inhibitory effects against molds, yeasts, and certain bacteria, though its efficacy against acid-resistant strains is relatively weak. The bacteriostatic activity is highly dependent on environmental pH levels, showing peak effectiveness at low pH concentrations and markedly reduced potency in alkaline conditions. Notably, this compound demonstrates excellent stability in food systems, resisting degradation from light exposure and thermal processing, which allows it to maintain its antibacterial properties throughout fruit and vegetable processing and storage. However, concerns over its chemical synthesis process and potential chronic toxicity have raised food safety regulatory issues and consumer health concerns, driving researchers to explore safer natural alternatives [2].

2.2 Current Situation of Sodium Dehydroacetate in Fruit and Vegetable Preservation

Sodium Dehydroacetate (DHA-S), a highly effective chemical preservative, remains crucial in fruit and vegetable processing and preservation, particularly for high-moisture, perishable produce. Its commercial applications include direct addition to processed foods like jams, preserved fruits, and pickled vegetables, or as a surface treatment agent for fresh-cut produce preservation. With its broad-spectrum antimicrobial properties, DHA-S effectively inhibits the growth of molds such as Penicillium and Aspergillus, as well as yeasts, thereby extending shelf life. In industrial production, DHA-S is often combined with other preservatives like potassium sorbate and sodium benzoate to create synergistic effects and reduce individual preservative usage, achieving superior preservation results within regulatory limits. Additionally, DHA-S's thermal stability enables post-thermal sterilization secondary preservation, such as in the final treatment of canned fruit and vegetable products [3].

However, with increasingly stringent food safety regulations and growing consumer concerns about health risks, the application of DHA-S is facing significant limitations. Regions such as the EU and the United States have established strict upper limits for its use in certain foods, while China's "National Food Safety Standard for Additive Usage" explicitly defines permitted applications and prohibits direct use in some fresh fruits and vegetables. These regulatory measures primarily address DHA-S's potential chronic toxicity risks, including endocrine system interference from metabolites and observed hepatorenal toxicity in animal studies. Concurrently, market trends show consumers increasingly favor "clean label" products-those free from synthetic preservatives-which further diminishes DHA-S's commercial acceptance. Although no fully equivalent alternatives currently exist that surpass DHA-S in both cost-effectiveness and performance, the industry has gradually shifted toward developing natural preservatives like lactic acid bacteria and plant extracts to meet health and sustainability demands. While DHA-S's role in fruit and vegetable preservation may gradually diminish, its transitional value remains significant-particularly given the current lack of mature natural alternatives for large-scale adoption [4].

2.3 Safety Risks and Regulatory Restrictions of Sodium Dehydroacetate

While sodium dihydroacetate demonstrates exceptional performance in food preservation, its potential safety hazards have drawn significant attention from global food safety regulators. Toxicological studies indicate that metabolites of DHA-S may exert chronic toxicity through mechanisms such as disrupting cellular redox balance and inducing DNA damage. Long-term consumption of foods containing DHA-S could increase hepatic metabolic burden, with animal experiments showing hepatocyte vacuolization and renal dysfunction at high doses. Moreover, the molecular structure of DHA-S resembles certain endogenous metabolites, potentially interfering with normal metabolic pathways through competitive inhibition-particularly posing heightened risks to children and individuals with compromised metabolic functions. These toxicological findings have prompted organizations like the International Agency for Research on Cancer to classify it as a "Substances of Concern for Further Assessment of Potential Hazard." Although not yet classified as carcinogenic, precautionary restrictions have become a regulatory trend [5].

Global regulatory frameworks exhibit differentiated approaches to DHA-S applications, but generally trend toward stricter standards. The European Food Safety Authority has established a daily intake limit of 1 mg/kg body weight through risk assessment, prohibiting direct use in fresh fruits and vegetables. In contrast, the U.S. Food and Drug Administration permits limited addition in certain processed foods, provided with clear labeling. China's GB 2760 standard initially permitted DHA-S in preserved foods like candied fruits and pickled vegetables, but has gradually narrowed its scope through revisions in recent years, reflecting the policy orientation of "reducing additives." This regulatory tightening stems not only from accumulating scientific evidence but also responds to consumers' growing demand for clean-label products. Notably, regulatory challenges also emerge in detection technology-its binding with food matrices may affect residue assessment accuracy, further complicating compliance. Looking ahead, as alternative technologies mature, DHA-S's role in the food industry may transition from "restricted use" to "phase-out," requiring a dynamic balance between food safety, technical feasibility, and industrial adaptability [6].

3. Potential Analysis of Lactic Acid Bacteria as Biological Preservative

3.1 Antibacterial Characteristics and Mechanism of Lactic Acid Bacteria

Lactic acid bacteria, as a group of microorganisms with significant biopreservative potential, derive their antibacterial properties primarily from complex metabolic activities and competitive inhibition against pathogenic microorganisms. These bacteria can produce various antimicrobial substances through carbohydrate fermentation, including organic acids, bacteriocins, hydrogen peroxide, and volatile compounds with bacteriostatic activity. The synergistic interaction of these metabolites forms a multi-layered antimicrobial defense system. Specifically, organic acids reduce environmental pH levels, directly inhibiting the growth of most spoilage and pathogenic bacteria while disrupting microbial cell membrane integrity, leading to intracellular proton gradient imbalance and inactivation of key enzymes. Bacteriocins demonstrate higher specificity by binding to specific receptors on pathogenic cell membranes, creating pore channels that induce intracellular leakage or interfering with critical steps in cell wall synthesis. Additionally, lactic acid bacteria inhibit spoilage bacterial colonization through nutrient competition and niche competition. This "biological competitive exclusion" effect plays a crucial role in regulating the microecology of fruit and vegetable surfaces [4].

A key area for exploration is the close relationship between lactic acid bacteria's antimicrobial spectrum and their strain-specific characteristics. Certain Lactobacillus plantarum and Lactobacillus casei strains not only inhibit common spoilage bacteria in fruits and vegetables but also demonstrate significant antagonistic effects against certain foodborne pathogens. The diversity of their mechanisms is further reflected in quorum sensing interference and biofilm inhibition-lactic acid bacteria can degrade pathogenic bacteria's auto-inducible signaling molecules, blocking the expression of virulence factors and biofilm formation. This multi-target, low-drug-resistance antimicrobial approach gives lactic acid bacteria a competitive edge over single-action chemical preservatives. However, the antimicrobial efficacy of different Lactobacillus strains is significantly influenced by environmental factors, necessitating precise regulation for their application in complex food systems. Future research should focus on elucidating the structure-activity relationships of specific strains' antimicrobial compounds and optimizing their delivery systems for fruit and vegetable preservation to fully leverage their biological preservation potential [6].

3.2 Effects of Lactic Acid Bacteria Metabolites on Fruit and Vegetable Quality

The metabolic byproducts generated by lactic acid bacteria during fruit and vegetable preservation not only inhibit spoilage microorganisms but also positively influence the sensory quality, nutritional value, and storage stability of these produce. The core mechanisms primarily manifest in three aspects: First, organic acids produced through lactic acid bacterial fermentation effectively regulate the pH-value of the surface microenvironment. This acidic condition not only suppresses the activity of spoilage-causing bacteria but also reduces the respiration intensity and enzymatic browning reactions in fruits and vegetables, thereby delaying the aging process. Second, specific bacterial strains secrete extracellular polysaccharides that form protective biofilms on the surface. This physical barrier reduces water evaporation to maintain tissue plumpness while blocking oxygen infiltration to inhibit oxidative deterioration. Third, certain metabolites such as γ-amino butyric acid and phenolic derivatives possess antioxidant properties, which can eliminate free radicals and protect heat-sensitive nutrients like vitamin C and polyphenols in fruits and vegetables [7].

It is noteworthy that the functional properties of lactic acid bacteria metabolites exhibit significant strain-dependent characteristics. For instance, certain lactic acid bacteria produce volatile esters that impart distinctive aromatic profiles to fruits and vegetables, while specific strains secrete proteases capable of breaking down pectin substances causing tissue softening, thereby maintaining product texture. This "metabolic regulation" mechanism enables lactic acid bacteria not only to extend shelf life but also actively enhance product quality, fundamentally differing from the bacteriostatic effects of chemical preservatives. However, the efficacy of metabolites is constrained by factors such as fruit/vegetable types and storage conditions-high moisture activity environments may dilute organic acid concentrations, while low-temperature storage can inhibit lactic acid bacteria metabolic activity. Future research should focus on deciphering synergistic mechanisms between specific fruit/vegetable strains and developing metabolic engineering approaches to optimize product profiles, achieving optimal balance between preservation effectiveness and quality enhancement [8].

3.3 Synergistic Effect of Lactic Acid Bacteria and Other Preservation Techniques

The application of lactic acid bacteria in fruit and vegetable preservation is not isolated. When synergistically integrated with physical, chemical, and biological preservation technologies, they can establish a more efficient composite preservation system. Physically, combining lactic acid bacteria with moderate low temperatures or modified atmosphere packaging allows low-temperature environments to delay excessive acidity caused by rapid bacterial metabolism while prolonging metabolic activity through suppressed host respiration. The controlled O_2/CO_2 ratio in modified atmosphere packaging complements the microaerophilic nature of lactic acid bacteria, effectively inhibiting aerobic spoilage bacteria while promoting targeted secretion of antimicrobial compounds. Chemically, when combined with natural antioxidants, lactic acid bacteria utilize biological antagonism to control microbial contamination, while the antioxidants block oxidative chain reactions. This "biological-chemical" dual defense mechanism creates a synergistic effect in maintaining fruit and vegetable coloration and texture. Of particular note is the combination of lactic acid bacteria with bacteriophages. Bacteriophages specifically target and lyse specific pathogens, while lactic acid bacteria maintain a broad-spectrum inhibitory microenvironment, achieving a dynamic balance between precise targeting and broad-spectrum defense.

From a molecular perspective, this synergistic effect stems from complementary action sites of multiple preservation factors. For instance, physical treatments like ultrasound or irradiation may slightly damage the fruit and vegetable surface structure, which paradoxically facilitates the penetration of lactic acid bacteria metabolites into tissues. Meanwhile, organic acids produced by lactic acid bacteria enhance the antibacterial activity of natural coating materials such as chitosan. However, technical antagonism risks should be guarded against-high-intensity irradiation might impair lactic acid bacteria activity, while residual chemical disinfectants could interfere with bacterial colonization. Future research should establish an "enhancement-reduction" evaluation model to predict compatibility of different technical combinations through computational simulations, while developing time-controlled release systems to optimize the interaction between lactic acid bacteria and preservation factors at various storage stages. This multi-technique synergy strategy not only reduces reliance on individual methods but also drives precision and personalized development in fruit and vegetable preservation.

4. Comprehensive Evaluation of Lactic Acid Bacteria as a Substitute for Sodium Dehydroacetate

4.1 Safety Comparison: Toxicology and Consumer Acceptance

In food safety evaluation, lactic acid bacteria demonstrate significant advantages as potential alternatives to sodium dehydroacetate, with their safety validated through extensive consumption history and systematic toxicological studies. From a toxicological perspective, lactic acid bacteria and their metabolites are generally considered safe. Their antibacterial mechanisms primarily involve competitive inhibition and metabolite regulation rather than the direct cytotoxic effects of chemical preservatives. Unlike DHA-S, which may cause liver and kidney dysfunction risks, lactic acid bacteria not only lack bioaccumulation but also exhibit potential probiotic effects through gut microbiota regulation in certain strains. The Codex Alimentarius Commission and national regulatory agencies impose significantly lower restrictions on lactic acid bacteria in food applications compared to chemical preservatives, reflecting high recognition of their safety. Notably, during fruit and vegetable preservation, lactic acid bacteria typically exist as inactivated forms or metabolite extracts, further reducing uncertainties associated with live bacterial cultures while retaining the preservative activity of their functional components.

From the perspective of consumer acceptance, lactic acid bacteria possess a natural "clean label" attribute that aligns with modern consumers 'dual expectations for "minimal additives" and "biological preservation". Market research indicates that consumers show significantly higher acceptance of foods labeled with "lactic acid bacteria extract" or "fermentation metabolites" compared to those containing chemical preservatives. This preference stems from the cognitive advantage of "naturalness" and associated health benefits. In contrast, synthetic preservatives like DHA-S, despite undergoing rigorous risk assessments, still trigger risk perception biases due to their "chemical synthesis" nature. However, the promotion of lactic acid bacteria preservation technology faces cognitive challenges, as some consumers may mistakenly believe it causes excessive sourness or texture changes in products. These misunderstandings require clarification through public education and technical improvements. Overall, when evaluated from both "safety" and "acceptance" dimensions, lactic acid bacteria demonstrate clear comparative advantages in replacing DHA-S, particularly among health-conscious consumer groups. This advantage provides a viable pathway for the food industry's clean label transformation.

4.2 Functional Comparison: Preservation Effect and Nutrient Retention

In functional evaluation dimensions, lactic acid bacteria and sodium dehydroacetate (DHA-S) exhibit fundamental differences in their preservation mechanisms, which directly influence their effectiveness in regulating fruit and vegetable quality. As a chemical preservative, DHA-S primarily functions through bacteriostatic effects to delay spoilage, but cannot actively participate in post-harvest physiological regulation of fruits and vegetables. In contrast, lactic acid bacteria demonstrate multi-target preservation capabilities: On one hand, the organic acids and bacteriocins produced during their metabolism effectively inhibit spoilage microorganisms; on the other hand, they mitigate oxidative damage and physiological aging by secreting antioxidants and inducing natural resistance mechanisms in fruits and vegetables. This dual-track mechanism of "bacteriostasis and physiological regulation" enables lactic acid bacteria-treated produce to outperform DHA-S-treated counterparts in sensory indicators such as firmness and coloration, particularly demonstrating more significant preservation effects for fruits with respiratory transition characteristics.

From the perspective of nutritional preservation, lactic acid bacteria demonstrate unique value-added effects. While DHA-S as a chemical additive can extend shelf life, it offers no protection for endogenous nutrients in fruits and vegetables, and may even accelerate the degradation of heat-sensitive components. In contrast, specific lactic acid bacterial strains not only preserve nutrients but also produce bioactive substances like B vitamins and γ-aminobutyric acid during fermentation, enhancing product nutritional density. For instance, Lactobacillus plantarum treatment significantly reduces enzymatic browning in fresh-cut apples while increasing total phenol content; short-lactobacillus-fermented fruit and vegetable juices show over 30% higher vitamin B12 levels. This synergistic "preservation-nutrition enhancement" effect is unachievable with chemical preservatives. However, the preservation efficacy of lactic acid bacteria remains challenging due to variations in strain characteristics, inoculation amounts, and environmental parameters. Standardized application requires strain selection optimization and process refinement to ensure functional stability. Overall, within the dual evaluation framework of "preservation-nutrition," lactic acid bacteria not only replace DHA-S's basic preservative function but also add extra health benefits to fruit and vegetable products, providing theoretical support for their application in functional food development.

4.3 Economy and Feasibility of Large-scale Application

In industrial applications, the economic viability and scalability of lactic acid bacteria replacing sodium dehydroacetate require comprehensive evaluation from a full industry chain perspective. From a production cost standpoint, while the initial investment in lactic acid fermentation technology exceeds that of chemical preservatives, its long-term operational costs demonstrate significant advantages: Firstly, lactic acid bacteria utilize agricultural by-products as low-cost culture media, enabling resource recycling. Secondly, with the maturation of high-density fermentation and immobilized cell processes, energy consumption per unit biomass has decreased by over 40% compared to a decade ago. Unlike DHA-S which is susceptible to fluctuations in petroleum feedstock prices, lactic acid bacterial production systems maintain more stable raw material supplies and align with carbon neutrality policy objectives. The multifunctionality of lactic acid bacterial preparations helps spread application costs, while their premium pricing effectively offsets some production expenses.

The core challenges in large-scale application lie in technical adaptability and standardized control. Current lactic acid bacteria preservation technology shows significant differences in effectiveness across fruit and vegetable categories. While achieving over 90% preservation efficiency for berries compared to DHA-S, its antibacterial efficacy for high-pH-value vegetables still requires optimization. This necessitates establishing strain libraries and process parameter databases tailored to different fruits and vegetables. Key technical hurdles include maintaining bacterial activity, ensuring uniform distribution, and compatibility with existing processing workflows. For instance, microencapsulation technology can address bacterial activity loss during pre-cooling, while electrostatic spraying systems enable precise application of bacterial solutions on fruit surfaces. From a market acceptance perspective, specialized lactic acid bacteria preparation suppliers in the EU and North America have already achieved product standardization meeting industrial demands. Although current preservation costs remain 15-20% higher than DHA-S, cost parity is expected within 3-5 years as economies of scale emerge and technologies advance. This substitution process requires not only technological innovation but also establishing comprehensive standards covering strain management, production processes, and application protocols to mitigate corporate risks during technology transition.

5. Conclusions

This study systematically analyzed the application prospects of lactic acid bacteria as a sodium dehydroacetate substitute in fruit and vegetable preservation. The research confirmed that lactic acid bacteria not only effectively maintain food safety but also enhance product functionality through their unique metabolic activities. Compared with traditional chemical preservatives, lactic acid bacteria offer advantages such as safety, environmental friendliness, and multifunctionality. However, key challenges in industrial application remain unresolved, including strain selection, process optimization, and cost control. Future research should focus on establishing standardized preservation systems using lactic acid bacteria and integrating them with other green technologies. This will provide more comprehensive biological preservation solutions for the food industry, advancing both food safety and the achievement of sustainable development goals.

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