Scientific and Social Research, 2025, Volume 7, Issue 11
https://ojs.bbwpublisher.com/index.php/SSR
Online ISSN: 2981-9946
Print ISSN: 2661-4332

Research Progress and Application Prospects of Preservation Technology for Bananas on the Tree

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Abstract: As a typical climacteric fruit, the rapid postharvest decay and deterioration of bananas pose a significant challenge to the global fruit and vegetable industry. Traditional postharvest preservation technologies face bottlenecks such as poor timeliness, pesticide residues, and high costs, prompting research focus to shift towards more forward-looking "on-tree preservation" technologies. This paper systematically reviews the latest research progress in preservation technologies for bananas on the tree, delving into the mechanisms of core technologies such as 1-methylcyclopropene (1-MCP) slow-release technology, functional bagging, plant growth regulators, and nutritional regulation from a molecular physiology perspective. Innovatively, a multi-level synergistic preservation theory is proposed, and a technological system framework is constructed. This paper comprehensively explores, for the first time, the cutting-edge topic of the potential impact of preservation treatments on the flavor metabolomics of bananas, thoroughly analyzing technological bottlenecks, risk-benefit considerations, and future directions. Finally, from the perspective of integrating green chemistry, smart materials, and intelligent agriculture, the paper anticipates trends towards precision, intelligence, and systematization in this field, aiming to provide a novel theoretical framework and technological pathway for breaking through the loss bottleneck in the banana industry.

Keywords: Banana; On-tree preservation; Mechanism of action; Synergistic preservation; Flavor metabolomics; Precision agriculture

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Online publication: December 12, 2025

1. Introduction

Bananas (*Musa nana Lour*.) are one of the most critical tropical fruits in the global trade system. According to

FAO statistics, the global annual production has remained stable at over 120 million tons in the past five years. China is the world's second-largest banana producer and importer, with an annual output exceeding 10 million tons. However, the climacteric process of bananas, driven by an endogenous ethylene burst after harvest, is extremely rapid, resulting in a shelf life of only 5–7 days at room temperature. This leads to a comprehensive pre- and post-harvest loss rate of 30%–50% in high-temperature and high-humidity production areas, causing staggering annual economic losses and becoming a core pain point restricting the sustainable development of the industry.

For a long time, post-harvest preservation technologies relied upon by the industry, such as chemical dipping, low-temperature cold chain, and controlled atmosphere storage, have played a certain role. However, their inherent limitations have become increasingly prominent in the context of contemporary green development and efficiency improvement: (1) There is immense pressure on timeliness, as the process from harvest to treatment must be completed within the "golden 24 hours", posing an extreme test to supply chain coordination; (2) There are food safety and ecological risks, as repeated use of post-harvest fungicides and ethylene inhibitors raises concerns about residues, and wastewater treatment poses environmental pressure; (3) The economic costs are high, as the energy consumption and equipment investment for the entire cold chain continuously compress the industry's profit margins.

To fundamentally break through the deadlock, research paradigms are undergoing a strategic transformation from "passive response" to "proactive intervention." On-plant preservation, as a disruptive source-control strategy, refers to the direct intervention in the ripening and senescence process of banana fruits on their mother plants during a critical window period when the fruits have reached physiological maturity but have not yet initiated ethylene self-catalytic synthesis. This is achieved through physical, chemical, or biological agronomic measures, thereby extending the harvestable period by several weeks. This technology not only provides producers with the flexibility to "harvest on demand" based on market conditions to maximize profits but also eliminates field losses caused by "premature harvesting" at the source and alleviates post-harvest logistical pressures. It serves as a key technological lever to drive the industry towards higher yields, superior quality, efficiency, ecological sustainability, and safety.

This paper aims to conduct a comprehensive and in-depth review of on-plant preservation techniques for bananas based on research findings from the past five years. The focus is not only on summarizing the technology itself but also on elucidating its mechanisms of action at the molecular and physiological levels, revealing the synergistic effects among different techniques, and systematically exploring, for the first time, the complex relationship between preservation treatments and the formation of fruit flavor and quality. By adding a "Discussion and Outlook" section, the paper delves into identifying technological bottlenecks and proposes forward-looking future development directions centered around intelligent materials and precision agriculture, with the goal of establishing a systematic theoretical and technological framework for on-plant preservation of bananas.

2. Mechanism of action and cutting-edge advances in preservation technology for banana trees

The ripening of banana fruit is a highly programmed biological process dominated by ethylene signaling, involving energy metabolism, cell wall degradation, pigment transformation, and the synthesis of flavor compounds. The essence of on-tree preservation technology lies in precisely regulating key nodes within this network through exogenous intervention, thereby delaying the initiation and progression of the climacteric phase.

2.1. Chemical regulation technology: From the core ethylene pathway to multi-target synergistic intervention

Chemical regulation remains a pioneering field in on-tree preservation research due to its direct action and significant effects, with its scope expanding from single ethylene inhibition to synergistic regulation of multiple signaling pathways.

2.1.1. Mechanism deepening and technological iteration of ethylene action inhibitor—1-Methylcyclopropene (1-MCP)

1-MCP efficiently blocks the transmission of ethylene signals downstream by irreversibly occupying ethylene receptors (ETR family proteins), making it the most clearly defined and effective core technology in current on-tree preservation systems.

Formulation innovation and precision application strategies: Challenges in field applications have spurred innovations in 1-MCP formulations. The α-cyclodextrin-embedded sustained-release tablets developed by Li Xueping et al. (2019) achieved sustained release for over 14 days in a bagged microenvironment, delaying the yellowing time of Brazilian bananas by 20–28 days, with significantly higher fruit firmness and vitamin C (Vc) content compared to the control [1]. Recent research has further focused on intelligent, responsive dosage forms. Costa et al. (2024) reviewed the technology of encapsulating 1-methylcyclopropene (1-MCP) in temperature-sensitive hydrogels, which can accelerate the release of active ingredients when ambient temperatures rise (indicating an increased risk of accelerated ripening), enabling "on-demand dosing" and representing a cutting-edge direction for future dosage form development [2]. In terms of application strategies, a precise judgment method based on the combination of fruit plumpness (75%–80%) and an effective accumulated temperature model has become crucial for achieving optimal preservation effects [3].

In-depth analysis of molecular physiological mechanisms: With the application of omics technologies, the mechanism of action of 1-MCP has been revealed at a deeper level. Wang et al. (2020), through transcriptomic analysis, found that 1-MCP treatment not only significantly downregulated the expression of key genes involved in ethylene biosynthesis, MaACS1 and MaACO1, but also inhibited the transcription levels of a series of cell wall-degrading enzyme genes (such as MaPG, MaPE, and MaExpansin), explaining its mechanism for maintaining fruit firmness at the molecular level [4]. More notably, the impact of 1-MCP on flavor metabolism has become a new research focus. Wang Weimin et al. (2022), utilizing GC-MS metabolomics technology, discovered that while high-concentration 1-MCP treatment effectively delayed softening, it also postponed the peak expression of MaATF1, a key gene involved in the synthesis of characteristic aroma compounds in bananas such as acetate esters and butyrate esters. This resulted in fruits that were yellow but lacking in aroma [5]. This reveals the inherent contradiction between preservation techniques and quality formation, providing precise targets for optimizing treatment parameters.

2.1.2. Synergistic potential of other plant growth regulators

Relying solely on 1-MCP may have limitations, as other plant hormones can intervene in ripening through different pathways, demonstrating potential for synergistic preservation.

Antagonistic regulation of gibberellin (GA3) and ethylene: As a growth-promoting hormone, GA3 exhibits antagonism with ethylene, a senescence-promoting hormone. Srivastava et al. (2017) confirmed that pre-harvest spraying of GA3 (100 mg/L) could delay the ripening of Grand Naine bananas by inhibiting ACO activity and enhancing the activity of antioxidant enzymes (SOD, CAT) [6]. Recently, research by Zhu et al. (2023) further revealed that GA3 can upregulate the expression of the MaCBR gene in banana fruits, which is responsible for maintaining chlorophyll stability, providing new evidence for the green-preserving effect of GA3 [7]. The combined use of 1-MCP and GA3 is considered an innovative strategy for synergistically controlling ripening from the dimensions of "signal blockade" and "physiological delay."

Homeostasis regulation of nitric oxide (NO) and reactive oxygen species (ROS): As a gaseous signaling molecule, NO regulates various physiological processes through protein S-nitrosylation modification. Research by Liu Zunying et al. (2020) demonstrated that pre-harvest application of the NO donor sodium nitroprusside (SNP) effectively delays banana ripening, exhibiting a synergistic effect when combined with 1-MCP [8]. Recent studies (Li et al., 2023) have revealed that this effect of NO partially stems from its ability to scavenge reactive oxygen species (ROS) and maintain mitochondrial functional homeostasis, highlighting the critical role of redox balance in fruit senescence [9].

Signal crosstalk between methyl jasmonate (MeJA) and salicylic acid (SA): As important stress hormones, MeJA and SA have also been found to interfere with ethylene signaling. Recent research (Chen et al., 2024) indicates that pre-harvest treatment with low concentrations of MeJA can enhance banana peel resistance by activating phenylpropanoid metabolism and partially inhibiting ethylene synthesis, providing new insights for the development of biogenic preservatives [10].

2.2. Physical protection technologies: From passive isolation to active and intelligent microenvironment regulation

Physical technologies serve as the cornerstone of chemical regulation, evolving beyond simple physical barrier functions to actively and intelligently regulate the fruit microenvironment.

2.3. Systematic upgrades in functional bagging technology

Bagging is a standard practice in banana production, and functional bagging represents the core of microenvironment management for preserving fruit on the tree.

Functional integration and material innovation: Modern functional bagging has evolved into a micro-ecosystem that integrates physical protection, ethylene adsorption, antibacterial and bacteriostatic properties, temperature regulation, and moisture permeability. The double-layer bag developed by Liu et al. (2021), which contains a potassium permanganate-activated carbon composite ethylene adsorbent and a chitosan-based antibacterial agent, reduced the ethylene concentration inside the bag by over 40% and decreased the incidence of anthracnose by more than 35% [11]. In recent years, the application of nanomaterials has further enhanced the performance of bagging. Silva et al. (2023) reviewed polyethylene films loaded with nano-silver or nano-zinc oxide, which not only exhibit higher antibacterial efficiency but also possess certain UV-blocking capabilities, more effectively delaying fruit senescence [12].

Maximizing synergistic effects: The combination of functional bagging and 1-MCP slow-release agents forms a "golden partnership" of "physical adsorption + chemical blockade." The semi-enclosed space created by bagging not only prolongs the action time of 1-MCP but also slightly inhibits respiration due to the low-oxygen environment inside, producing synergistic enhancement.

2.4. Nutritional and agronomic regulation: Building the fruit's intrinsic "stress resistance"

Strengthening tree vigor and intrinsic fruit quality through cultivation management serves as the physiological foundation for the efficient implementation of on-tree preservation techniques.

The fundamental role of calcium (Ca) nutritional fortification: Calcium is a crucial structural component of cell walls and cell membranes. Research by Zhang et al. (2019) demonstrated that pre-harvest calcium treatment effectively delays fruit softening by increasing the content of covalently bound pectin in the cell wall and upregulating the expression of MaPME and MaPG inhibitors [13]. Recent research (Kumar et al., 2024) has further revealed that calcium signaling also interacts with the ethylene signaling pathway, and Ca^{2+} may influence the activity of ethylene receptors by regulating calmodulin, providing a new perspective on the preservation mechanism of calcium [14].

The synergistic beneficial effects of silicon (Si) and boron (B): In addition to calcium, the roles of trace elements such as silicon and boron have also garnered attention. A recent study (Gong et al., 2023) found that pre-harvest foliar spraying of potassium silicate enhanced the mechanical strength of banana peels and reduced disease incidence, with silicon deposition in the cell wall forming a physical barrier [15]. Boron, on the other hand, contributes to the integrity of cell wall structure and works synergistically with calcium and silicon to collectively construct a robust fruit defense system.

To visually illustrate the combined mechanisms of the aforementioned technologies, the study has constructed the following schematic diagram (**Figure 1**). Additionally, a comparative analysis of the main on-tree preservation technology systems for bananas has been conducted (**Table 1**).

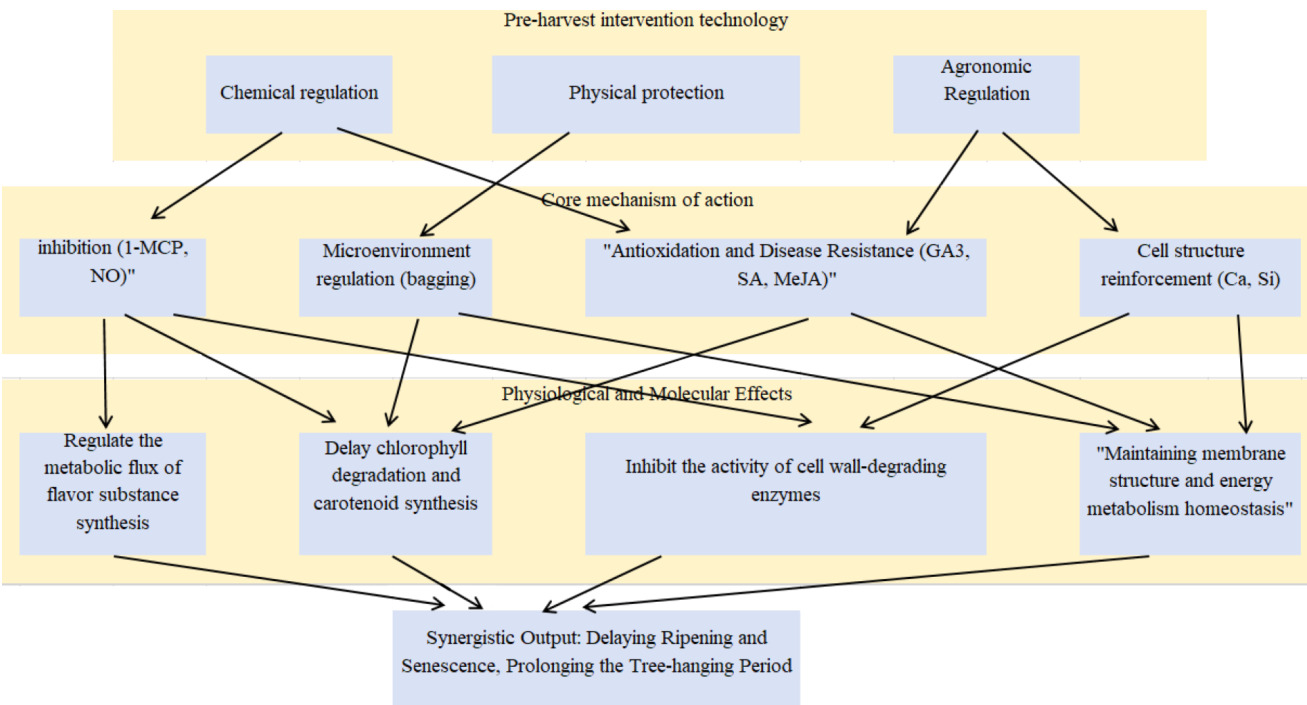

Figure 1. Schematic diagram of the combined mechanisms of on-tree preservation technologies for bananas

Table 1. Comparative analysis of main preservation technology systems for bananas on the tree

Technology Type	Representative Measures	Mechanism of Action	Advantages	Limitations	Development Trend
Chemical Regulation	1-MCP sustained-release agent	Competitively inhibits ethylene receptors (ETR1/2), blocking ripening signals	Most effective, long duration	High cost, may inhibit flavor compound synthesis	Evolving towards intelligent responsive sustained-release agents
	Gibberellin (GA3) spraying	Antagonizes ethylene, delays senescence, enhances antioxidant defense system	Environmentally friendly, easy to use	Effectiveness affected by climate, stability relatively poor	Used as synergist in combination with 1-MCP
	Nitric oxide (NO) donors	Nitrosylates target proteins (e.g., ACO), scavenges ROS	Gas molecule, good permeability, low toxicity	Requires precise dose control, poor field stability	Gaining attention as signaling molecule regulators
Physical Protection	Functional bagging	Adsorbs ethylene, antibacterial, regulates temperature/moisture, creates optimal micro-environment	Multiple protections, green and safe	High initial investment cost, generates plastic waste	Integration with nanotechnology and biodegradable materials
Nutritional/ Agronomic Regulation	Calcium/Silicon/ Boron nutrient fortification	Stabilizes cell wall/ membrane structure, enhances physical resistance	Fundamentally improves fruit quality and storage tolerance	Slow effect, requires long-term implementation as a basic measure	Focus on signal crossover and synergistic mechanism research
	Moderate water stress	Induces stress resistance signals (e.g., ABA), delays metabolism	Water-saving, low cost	Narrow operational window, risk of yield reduction or uneven quality, high risk	Integration with precision irrigation technology

3. Discussion and prospects

3.1. Technological integration and synergistic effects: From simple superposition to system optimization

Current research has clearly demonstrated that it is difficult for any single technology to address all the challenges associated with preserving bananas on the tree [16]. The breakthrough point for future advancements lies in the systematic integration and synergy of technologies. For instance, the combination of "calcium nutrition enhancement + functional bagging + 1-MCP slow-release agent" constructs a three-dimensional defense system by enhancing the fruit's intrinsic resistance, optimizing the external microenvironment, and precisely inhibiting the initiation signals of ripening at three different levels, respectively [17]. However, technological integration is not a simple superposition, as there are complex physiological interactions underlying it. For example, the cross-talk between calcium signaling and ethylene signaling may affect the efficacy of 1-MCP; the microenvironment inside the bagging (O_2/CO_2 ratio) may alter the fruit's energy metabolism state, thereby influencing its response to growth regulators [18]. Therefore, future research should employ systems biology approaches to uncover the global physiological response networks under different technological combinations, thereby maximizing synergistic effects and avoiding antagonistic actions [19].

3.2. Deepening of quality connotations: Flavor and nutritional assurance beyond shelf life

Traditional freshness preservation research primarily aims to extend shelf life, whereas the modern fruit and vegetable industry demands that preservation technologies must, to the greatest extent possible, safeguard or even enhance the flavor and nutritional quality of the fruits [20]. The potential inhibition of flavor compound synthesis by 1-MCP, as mentioned in this review, represents a classic "freshness preservation-quality" conflict. This necessitates the incorporation of flavor metabolomics and nutritional quality analysis into the evaluation system for preservation technologies. By studying the impacts of different preservation treatments on sugar metabolism, acid metabolism, volatile esters, and phenolic compound synthesis pathways, researchers can create a regulatory map of "preservation treatment-quality formation" to precisely define the quality safety windows for each technology. This implies that the future goal of on-tree preservation will be to upgrade from "keeping fruits from rotting" to "keeping them from rotting while they are at their peak flavor."

3.3. Technological economic efficiency and industrial promotion models

Even the most advanced technology will struggle to be implemented if it is not economically viable. The costs of 1-MCP controlled-release agents and functional fruit bags remain barriers for scattered small-scale farmers. Therefore, conducting a detailed techno-economic analysis to quantify the relationship between technological inputs and the benefits derived from staggered market entry and reduced losses is crucial for persuading growers to adopt these technologies. In terms of promotion models, it is essential to vigorously develop specialized agricultural service organizations that provide socialized services ranging from technical guidance to unified pest and disease control, thereby reducing the learning costs and investment risks for individual farmers. Simultaneously, exploring market mechanisms that offer "premium prices for premium quality" will enable high-quality bananas produced using on-tree preservation technologies to command brand premiums, fostering a virtuous cycle of "technological investment—quality enhancement—increased revenue—further technological investment."

3.4. Green sustainable development and circular economy

Environmental sustainability is an enduring theme in technological development. Currently, on-tree preservation technologies still face issues such as "white pollution" caused by disposable plastic fruit bags and the environmental fate of chemical agents. Future research and development must focus on:

Degradable bagging materials: Develop fully degradable bagging materials based on biobased substances such as polylactic acid (PLA) and cellulose, while retaining or enhancing their functionality.

Biogenic preservatives: Vigorously develop preservation solutions based on biostimulants such as plant extracts, probiotics, and oligosaccharides to reduce reliance on synthetic chemicals.

Ecological risk assessment: Systematically evaluate the residues, degradation products, and ecological toxicity of substances like 1-MCP in soil-water ecosystems to provide a scientific basis for their safe use.

4. Conclusions and future prospects

The preservation technology applied directly to banana trees offers a revolutionary solution for reducing losses and enhancing efficiency in the industry by advancing the intervention nodes. This paper systematically reviews the technological progress in this field and provides an in-depth analysis from molecular physiology to industrial applications. The conclusions are as follows: First, chemical regulation centered on 1-MCP slow-release technology, whose mechanism of action has delved into the transcriptomic and metabolomic levels, will evolve towards intelligent responsive formulations in the future. Second, functional bagging, as a physical preservation carrier, is integrating with nanotechnology and degradable materials to upgrade towards intelligence and greenness. Thirdly, nutritional and agronomic regulation serves as the foundation of the technological system, laying the groundwork for the efficient implementation of other techniques by enhancing fruit quality. Fourthly, the synergistic integration of technologies, the deepening of quality connotations, the improvement of economic feasibility, and environmental sustainability are key factors determining the future success or failure of this technology.

Looking ahead, the on-tree preservation technology for bananas will exhibit three major integration trends: Firstly, the integration of technology and materials: applying the latest advancements in new material science (such as nanomaterials, hydrogels, and biodegradable plastics) to the development of formulations and bagging materials, thereby creating unprecedented preservation functions. Secondly, the integration of science and engineering: combining knowledge from plant physiology and molecular biology with agricultural engineering technology and environmental sensing technology to develop an Internet of Things-based decision support system for on-tree preservation. This system automatically makes decisions and executes optimal treatment plans by monitoring orchard environmental conditions and fruit physiological indicators in real time. Thirdly, the integration of production and market: establishing a quality traceability system through technologies like blockchain, transforming on-tree preservation technology into a "quality ID card" for branded bananas, and achieving precise value transmission from the field to the dining table.

Ultimately, on-tree preservation of bananas will evolve from a mere technological concept into an intelligent orchard precision management system that integrates multiple disciplines and covers the entire supply chain, leading the global banana industry into a new era of high quality, high efficiency, high profitability, and sustainable development.

Funding

Key R&D Program of Hainan Province (ZDYF2017060); Basic Research Fund for Central Public Research Institutes (1630082022001, 1630082016002); R&D projects commissioned by enterprises through industry-university-research cooperation (CATASATC-2023-306)

Disclosure statement

The authors declare no conflict of interest.

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