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Biochemical challenges in post-harvest banana storage and their role in food security

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Abstract

Banana (*Musa spp.*) is among the most widely cultivated fruits globally, serving as a critical source of nutrition and income for millions of people in tropical and subtropical regions. Despite its economic and dietary importance, post-harvest losses of banana remain significant, with estimates ranging from 20-50% in some developing regions. The biochemical processes governing banana ripening, such as starch hydrolysis, enzymatic browning, ethylene biosynthesis, and nutrient degradation, play central roles in reducing storage life and marketability. These biochemical changes are accelerated by factors such as temperature, humidity, mechanical injury, and microbial infection, making banana one of the most perishable fruits in the supply chain. Technological interventions including cold storage, modified atmosphere packaging, ethylene inhibitors, antioxidant treatments, and biotechnological innovations have shown promise in mitigating post-harvest deterioration. However, challenges persist, especially in resource-limited contexts where infrastructure and technologies are insufficiently accessible. This paper comprehensively examines the biochemical mechanisms underlying post-harvest banana deterioration, explores factors contributing to these changes, and evaluates mitigation strategies. Finally, the broader implications for food and nutritional security are discussed, with emphasis on minimizing losses across the supply chain to enhance sustainability and resilience in banana-dependent communities.

Keywords: Biochemical challenges, post-harvest banana storage, food security, starch hydrolysis

Introduction

Banana (*Musa spp.*) is the world's fourth most important food crop after rice, wheat, and maize, with global production exceeding 125 million tonnes annually [1]. The fruit serves as a staple food and cash crop in many developing countries, particularly in Africa, Asia, and Latin America, where it provides essential carbohydrates, minerals, and vitamins. Bananas are consumed fresh or processed into chips, flour, beverages, and baby foods, reflecting their socio-economic and nutritional significance [2]. In addition, the banana industry sustains livelihoods for millions of smallholder farmers, traders, and laborers worldwide [3].

Despite its importance, banana is highly perishable and prone to rapid biochemical and physiological deterioration following harvest. Post-harvest losses are estimated at 25-40% globally, and in some rural markets may exceed 50% [4]. Such losses compromise food availability, reduce farmer incomes, and exacerbate food insecurity, particularly in regions with limited storage and distribution infrastructure. Bananas' climacteric nature—characterized by a burst of respiration and ethylene production during ripening—further accelerates senescence, shortening their shelf life [5]. This creates considerable challenges for producers, traders, and policymakers seeking to balance supply, demand, and nutritional needs.

Biochemical processes are at the core of post-harvest banana deterioration. Enzymatic browning, starch-to-sugar conversion, ethylene biosynthesis, and oxidative stress contribute to textural softening, color changes, and nutrient degradation [6]. These changes not only reduce consumer appeal but also alter the fruit's nutritional quality. Understanding these processes is critical for designing effective interventions that extend shelf life while preserving quality. Moreover, addressing post-harvest biochemical challenges contributes directly to global food security by reducing waste, increasing marketable yield, and enhancing nutritional value.

This paper aims to: (1) examine the biochemical basis of post-harvest banana deterioration; (2) analyze factors contributing to biochemical instability; (3) evaluate technologies and practices for mitigating losses; and (4) discuss the implications of these challenges and interventions for food security. The hypothesis is that mitigating biochemical deterioration during banana storage can substantially enhance food and nutritional security by reducing post-harvest losses and improving marketability.

Biochemical Basis of Post-Harvest Changes

Enzymatic Browning

Enzymatic browning is one of the most recognizable biochemical changes during banana storage. This process occurs when phenolic compounds are oxidized by polyphenol oxidase (PPO) and peroxidase (POD) enzymes to form quinones, which polymerize into brown pigments [7]. Browning is accelerated by mechanical injury, oxygen exposure, and microbial infection. Peel browning reduces consumer acceptance, while pulp discoloration diminishes processing value [8]. Controlling enzymatic activity through antioxidants, controlled atmospheres, or enzymatic inhibitors remains a central challenge in banana storage.

Starch to Sugar Conversion

Banana ripening involves dramatic biochemical changes in carbohydrate metabolism. Starch, which constitutes up to 20-25% of the pulp in unripe bananas, is hydrolyzed into simple sugars (glucose, fructose, sucrose) under the action of amylases and invertases [9]. This conversion enhances sweetness and palatability but also accelerates softening, reducing mechanical integrity during transport [10]. Excess sugar accumulation also provides a substrate for microbial spoilage.

Ethylene Biosynthesis and Ripening

Ethylene plays a central role in banana ripening. The biosynthesis of ethylene involves conversion of S-adenosylmethionine to 1-aminocyclopropane-1-carboxylic acid (ACC) by ACC synthase, and then to ethylene by ACC oxidase [11]. Ethylene stimulates respiratory activity and activates enzymes responsible for cell wall degradation, chlorophyll breakdown, and aroma compound synthesis [12]. High ethylene sensitivity in bananas accelerates senescence, shortening post-harvest storage life.

Nutrient Degradation

Nutrient degradation further reduces banana quality during storage. Vitamin C, one of the most abundant antioxidants in bananas, is highly sensitive to oxidative stress and declines significantly during ripening [13]. Polyphenols, carotenoids, and flavonoids also undergo enzymatic and non-enzymatic degradation, reducing the fruit's nutritional value [14]. Such losses are critical from a food security perspective, as bananas are often consumed in regions with limited dietary diversity.

Factors Contributing to Biochemical Deterioration

Temperature and Humidity

Temperature is a major determinant of post-harvest banana physiology. Optimal storage temperatures range between 13-15 °C; below this, bananas suffer chilling injury characterized by peel blackening, pitting, and uneven ripening [15]. High humidity accelerates microbial growth and enzymatic activity, while low humidity causes desiccation and shriveling. Maintaining the correct balance is thus critical but challenging in tropical climates.

Mechanical Injury and Microbial Infection

Handling and transportation expose bananas to bruising, which disrupts cell structures, releases enzymes, and accelerates biochemical reactions such as browning and starch hydrolysis [16]. Injuries also provide entry points for microbial pathogens like *Colletotrichum musae* (anthracnose) and *Fusarium spp.*, which exacerbate biochemical and physical deterioration [17].

Storage Atmosphere

The composition of the storage atmosphere influences respiration and ripening. Elevated oxygen enhances oxidative stress, while excess carbon dioxide can suppress enzymatic activity but may induce off-flavors [18]. Modified atmosphere packaging (MAP) aims to optimize gas balance, but improper application can disrupt normal biochemical pathways and result in uneven ripening.

Reactive Oxygen Species (ROS)

ROS such as hydrogen peroxide and superoxide anions accumulate during ripening and stress, damaging lipids, proteins, and nucleic acids [19]. Bananas have antioxidant defense systems (superoxide dismutase, catalase, peroxidase), but these often become overwhelmed under suboptimal storage conditions, accelerating senescence [20].

Technological Interventions in Mitigating Biochemical Losses

Cold Storage and Modified Atmosphere Packaging

Cold storage slows metabolic and enzymatic processes, extending banana shelf life. However, the risk of chilling injury necessitates precise temperature management [21]. Modified atmosphere packaging, involving altered oxygen and carbon dioxide concentrations, reduces respiration rates and delays ripening [22]. When combined, these methods significantly mitigate biochemical deterioration.

Use of Inhibitors

Chemical inhibitors such as 1-methylcyclopropene (1-MCP) bind to ethylene receptors, delaying ripening by inhibiting ethylene perception [23]. Antioxidants such as ascorbic acid, citric acid, and plant extracts reduce enzymatic browning by scavenging free radicals or inhibiting PPO activity [24]. These approaches are increasingly used in commercial supply chains, though regulatory and consumer acceptance challenges persist.

Biotechnological Approaches

Genetic engineering and molecular breeding offer new avenues for controlling post-harvest biochemistry. Transgenic bananas with reduced PPO activity or altered ethylene biosynthesis have been developed to extend shelf life [25]. RNA interference (RNAi) techniques targeting ripening-related genes also show promise [26], though adoption is limited by ethical and market acceptance concerns.

Role of Nanotechnology

Nanomaterials such as nano-clays, chitosan nanoparticles, and edible nano-coatings are being explored to enhance banana storage. These coatings act as semi-permeable barriers, reducing respiration and moisture loss while carrying active agents such as antimicrobials or antioxidants [27]. Early trials indicate significant potential for minimizing biochemical losses and improving storability.

Implications for Food Security

The biochemical challenges of post-harvest banana storage directly affect global food security. Losses reduce marketable yield, undermine farmer incomes, and restrict consumer access to nutritious food. In sub-Saharan Africa, where bananas are a staple food, post-harvest deterioration undermines both caloric intake and micronutrient availability [28]. For smallholder farmers, lack of access to cold storage and modern packaging exacerbates losses, perpetuating poverty cycles.

Addressing these challenges through improved post-harvest technologies enhances food availability, reduces economic losses, and strengthens resilience in food systems. Moreover, by preserving nutritional compounds such as vitamin C and polyphenols, interventions ensure that bananas contribute effectively to dietary quality, especially in vulnerable populations [29]. At a global scale, reducing post-harvest banana losses contributes to the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production) [30].

Conclusion

Banana is a critical food and cash crop worldwide, but its high perishability poses major challenges for post-harvest storage. Biochemical processes including enzymatic browning, starch hydrolysis, ethylene biosynthesis, and nutrient degradation drive rapid deterioration, compounded by temperature stress, mechanical injury, and microbial infection. These losses have profound implications for food and nutritional security, especially in regions reliant on bananas as dietary staples. Technological interventions—ranging from cold storage and MAP to inhibitors, biotechnology, and nanotechnology—offer promising solutions but require broader accessibility and adaptation for resource-limited settings. Strengthening banana post-harvest management systems is essential for reducing food waste, improving nutritional outcomes, and supporting global food security.

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