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Study on Typical Food Spoilage Mechanisms and Preservation Technologies

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Abstract. Food preservation plays a vital role in reducing food loss and ensuring global food security. Employing a literature review approach, this paper synthesizes recent domestic and international studies on food preservation. The primary objects of study include plant-based foods and meat products, which exhibit distinct spoilage mechanisms. Plant-based foods are classified into climacteric and non-climacteric types. Climacteric fruits experience a sharp increase in respiration due to ethylene release, thereby accelerating ripening and senescence; non-climacteric fruits continuously generate reactive oxygen species (ROS) after maturity, resulting in membrane disruption and increased susceptibility to microbial invasion. Meat spoilage is mainly induced by microbial proliferation, enzymatic reactions, and lipid oxidation. Accordingly, preservation typically involves refrigeration, vacuum packaging, and antimicrobial treatments. The results indicate that effective preservation strategies must be tailored to the specific spoilage mechanisms of different food categories. This study contributes to understanding the current state of food preservation technologies and offers valuable insights for the future development of green, low-cost, and widely applicable preservation methods.

Keywords: food preservation, spoilage mechanisms, fruit preservation, meat preservation, green preservation technologies

1. Introduction

Food spoilage and deterioration are among the core causes of global food loss. Statistics show that more than one-third of global food production is lost each year due to spoilage, which not only leads to substantial economic waste but also exacerbates global food security challenges. However, research on food preservation still contains certain gaps. Traditional preservation methods confront drawbacks such as high cost and low efficiency, while the hazards of food spoilage extend beyond food loss to pose safety issues and environmental impacts. Therefore, identifying efficient, safe, and green preservation strategies is of great significance.

Thus, this paper adopts a literature review method to systematically summarize recent domestic and international progress in the spoilage mechanisms of major food categories and corresponding preservation technologies. It further proposes optimization directions for traditional preservation methods and suggestions for emerging green preservation technologies, with the aim of providing

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references for improving food preservation efficiency and developing green, low-cost preservation approaches.

2. Spoilage mechanisms and preservation technologies for plant-based foods

2.1. Climacteric fruits

2.1.1. Spoilage mechanism

Plants are generally classified into climacteric and non-climacteric types. The ripening and rotting of climacteric fruits mainly depend on ethylene biosynthesis. Specifically, the amino acid L-methionine is converted into S-adenosyl-L-methionine (SAM), a major methyl donor in plant metabolism [1]. Subsequently, ACC synthase (ACS) in the cytosol catalyzes SAM into 1-aminocyclopropane-1-carboxylic acid (ACC), with 5′-methylthioadenosine (MTA) as a by-product. Finally, ACC is oxidized by ACC oxidase (ACO) in the presence of oxygen to produce ethylene. Once synthesized, ethylene binds to receptor proteins on the cell membrane [2]. Prior to ripening, these receptors remain active and inhibit downstream signaling components EIN2 and EIN3/EIL through the Raf-like kinase CTR1, thereby supporting fruit growth and development [3]. Upon the onset of ripening, ethylene binds to the receptors, suppresses CTR1 activity and activating the EIN2–EIN3/EIL pathway, ultimately resulting in cell wall degradation, pigment changes, and aroma formation [4,5]. In summary, the primary driver of spoilage in climacteric fruits is ethylene synthesis and signaling, which accelerates the postharvest ripening process beyond the edible stage.

2.1.2. Preservation mechanism

As ethylene is the primary regulatory hormone in the ripening of climacteric fruits, inhibiting ethylene signaling or biosynthesis is a core strategy for extending their shelf life. 1-methylcyclopropene (1-MCP), an efficient competitive inhibitor of ethylene receptors, is one of the most widely used preservation methods. It binds irreversibly to ethylene receptors, blocking signal transduction and delaying ripening and decay. Research indicates that preharvest spraying of 1-MCP can reduce fruit drop and delay ethylene production [6]. Postharvest 1-MCP treatment also extends shelf life. α-cyclodextrin powder dissolves in water to release gaseous 1-MCP. With approximately 100 times higher affinity for ethylene receptors than ethylene itself. While a single application is often sufficient for short-term storage, the effect diminishes as plants synthesize new receptors, necessitating repeated treatments for long-term preservation.

Additionally, Controlled Atmosphere (CA) storage regulates the concentrations of oxygen, carbon dioxide, and humidity levels to slow respiration and delay ripening. Studies indicate that fruit respiration decreases significantly when the oxygen concentration falls below 8% [7]. Properly elevated CO_2 levels further inhibit ripening-related enzyme activity and microbial growth. Low temperatures suppress ethylene biosynthesis, while a relative humidity of 85–95% reduce water loss and microbial proliferation [8]. Traditional CA uses fixed low-oxygen levels, but excessively low oxygen can induce anaerobic respiration, causing ethanol and acetaldehyde and damaging quality. To address this limitation, researchers have developed Dynamic Controlled Atmosphere (DCA) storage, which adjusts oxygen concentration in real time based on fruit physiological responses, preventing low-oxygen injury while maximizing flavor preservation [9].

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2.2. Non-climacteric fruits

2.2.1. Spoilage mechanism

Spoilage in non-climacteric fruits mainly occurs during maturity and is closely associated with the accumulation of reactive oxygen species (ROS). Approximately 1% of oxygen consumed by plants is converted into ROS, including singlet oxygen, superoxide anions, and hydrogen peroxide [10]. During postharvest storage, metabolic imbalance can lead to excessive ROS production exceeding the clearance capacity, causing membrane damage. Singlet oxygen exhibits high reactivity with double bonds in organic compounds, directly impairing membrane structure. Hydroxyl radicals, recognized as the most reactive ROS, possess unpaired electrons and readily attack biomolecules. Due to the lack of specific scavenging enzymes for these radicals, they cause irreversible oxidative damage. Consequently, the excessive ROS accumulation triggers oxidative stress, disrupts membrane integrity and metabolism, and ultimately induces cell death. This process is manifested in visible spoilage symptoms such as fruit softening, browning, and spoilage.

2.2.2. Preservation technologies

Since ethylene is not the primary factor driving spoilage in non-climacteric fruits, current preservation research focuses on edible coatings and natural antimicrobial and antioxidant substances. Edible coatings are composed of biopolymers such as chitosan, sodium alginate, pectin, gelatin, carboxymethyl cellulose, and nanocellulose, which form a semi-permeable film to retard metabolic activity. For example, Hernández-Muñoz et al. developed a chitosan–calcium composite coating that effectively maintained strawberry firmness and soluble solid content while inhibiting the growth of Botrytis cinerea [11].

Additionally, the incorporating natural active substances such as essential oils and polyphenols enhances the coating’s antimicrobial and antioxidant properties. These compounds disrupt microbial membranes and inhibit enzymes such as PPO and POD, thereby extending shelf life of non-climacteric fruits.

3. Spoilage mechanisms and preservation technologies for meat products

3.1. Spoilage mechanisms

Unlike plant-based foods, which primarily spoil through physiological metabolic processes, animal-based foods spoil mainly due to external microbial contamination and complex internal biochemical reactions. Therefore, their spoilage mechanisms and the focus of preservation strategies differ significantly.

3.1.1. Bacterial metabolism

Bacterial metabolic activity is the primary driver of meat spoilage, encompassing both intracellular metabolic regulation and extracellular enzyme secretion [12]. Intracellularly, bacteria express functional genes and proteins to adapt to environmental stress. For example, under low-temperature conditions, lactic acid bacteria activate cold-shock response pathways, oxidative stress defense systems, and glycolytic metabolism, producing acetic acid and diacetyl, key off-flavor compounds regulated by specific metabolic genes [13]. Additionally, these bacteria accelerate acid and gas production via CcpA-dependent carbon catabolite repression.

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Extracellularly, spoilage bacteria secrete cold-active proteases and lipases that degrade meat tissue components. The synthesis of these hydrolytic enzymes is regulated by genes such as aprX and lipA, and they are secreted through type I and type II secretion systems. Certain Pseudomonas species regulate biofilm formation and enzyme secretion through AHL-based quorum sensing [14].

3.1.2. Lipid oxidation

Lipid oxidation constitutes another major spoilage pathway, including auto-oxidation, enzymatic oxidation, and photo-oxidation. During auto-oxidation, ROS attack the double bonds in unsaturated fatty acids, generating alkyl radicals and hydroperoxides that trigger chain propagation reactions [15]. The final products cause discoloration and off-odors in meat [16]. Photo-oxidation proceeds more rapidly, as pigments such as myoglobin act as photosensitizers to produce singlet oxygen, which directly oxidizes fatty acids [17]. Enzymatic oxidation, by contrast, is catalyzed by lipoxygenase, leading to the formation of conjugated dienes and hydroperoxides as key intermediate products [18].

3.2. Preservation technologies

Meat preservation technologies are designed to inhibit microbial growth and delay physicochemical deterioration,, and can be mainly divided into two categories: physical preservation and chemical preservation. Physical preservation achieves its effects mainly by regulating environmental conditions. Refrigeration leverages low temperature to effectively suppress the proliferation of most microorganisms and reduce enzyme activities, thereby maintaining meat quality for a short term. Freezing converts the majority of water in meat into ice crystals, which inhibits microbial growth and enzyme activity.

Rapid freezing forms small ice crystals, minimizing muscle fiber rupture and drip loss during thawing, and compared with slow freezing can better preserve meat quality. Drying reduces the water content of meat to inhibit microbial proliferation. In addition to extending shelf life, this method also enhances meat flavor and has become an important modern processing technique. Curing is a core chemical preservation approach: by adding salt, sugar, nitrate or nitrite and other substances to lower water activity and inhibit microbial growth, this method can improve meat flavor while extending shelf life. In addition, antioxidants such as ascorbic acid and their salts are commonly incorporated to enhance meat's antioxidant capacity and antimicrobial activity.

4. Limitations of existing preservation technologies

4.1. Limitations of 1-MCP

The preservative efficacy of 1-MCP varies substantially across fruit varieties, with some fruits exhibiting weak or short-lived responses that restrict its practical application. As new ethylene receptors form, repeated treatment becomes necessary. Additionally, low temperatures may also alter fruit response to 1-MCP, causing potential injury.

4.2. CA/DCA storage

CA storage is unsuitable for certain fruits such as bananas and watermelons. Its effectiveness depends on precise gas control; excessive CO_2 or insufficient O_2 can inhibit normal respiratory

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metabolism and trigger physiological disorders. DCA storage requires continuous real-time monitoring, resulting in increased energy consumption and costs.

4.3. Edible coatings

Most natural polymers have limited barrier capacity against water vapor and gases. Enhancing barrier properties may restrict respiration, causing off-flavors. Coating durability and adhesion vary across fruit surfaces, limiting industrial applicability.

4.4. Limitations of meat preservation technologies

Each method has drawbacks: drying processes can cause nutrient loss and flavor degradation; high-temperature treatments accelerate lipid oxidation; slow freezing induces muscle fiber rupture; and repeated freezing-thawing cycles fail to eliminate microbial risks. Nitrate-based curing produces carcinogenic nitrosamines.

In summary, future development should focus on multi-factor synergistic preservation and material innovation. Combining mild treatments can retain natural quality, while novel biopreservatives and green physical technologies are expected to meet consumer demand for healthy foods.

5. Conclusion

Based on a comprehensive review of existing literature, this paper systematically summarizes the spoilage mechanisms and corresponding preservation strategies for three typical food categories: climacteric fruits, non-climacteric fruits, and meat products, covering chemical, physical, and biological preservation approaches. However, existing methods still suffer from limitations such as high cost, quality degradation, and varietal dependence. Future research should focus on improving material performance and integrating multiple technologies to balance nutritional retention, flavor maintenance, and shelf-life extension.

This study has certain limitations. It focuses on typical food categories and does not fully encompss special fruit and vegetable types with unique physiological traits, which may affect the generalizability of the conclusions. Additionally, the analysis is mainly qualitative, lacking quantitative evaluation of key indicators such as energy consumption and environmental impact. Future studies could incorporate economic assessment to support evidence-based decision-making.

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