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Hexanal – A molecular solution for fresher produce

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Abstract

Post-harvest losses in the fresh produce sector pose a critical threat to global food security. This issue is exacerbated in developing countries were inadequate infrastructure and storage facilities impact smallholder farmers. To address this, the potential of hexanal as a postharvest preservation agent has been investigated. Hexanal, a natural compound, inhibits phospholipase D, an enzyme critical to fruit ripening and senescence. Both pre- as well as post-harvest applications of hexanal have demonstrated efficacy in extending shelf life and maintaining produce quality. Pre-harvest treatments, including enhanced freshness formulations (EFFs) containing hexanal, have improved fruit retention, quality, and disease resistance. Post-harvest techniques such as dipping and vaporization have effectively delayed ripening and reduced microbial growth. While challenges related to hexanal volatility persist, advancements in delivery systems offer promising solutions. The integration of hexanal into comprehensive post-harvest management strategies holds the capacity to considerably reduce food waste and enhance the quality and availability of fresh produce, benefiting farmers and consumers globally.

Keyword: hexanal, shelf-life, post-harvest, phospholipase D, nanotechnology

Introduction

Post-harvest losses in the fresh produce sector represent a significant challenge to global food security. Paradoxically, despite remarkable agricultural achievements, a staggering 33.33% which is approximately one in three of the world's food is squandered, with fruits and vegetables accounting for a large share of this unacceptable waste. This phenomenon is particularly acute in developing countries, where post-harvest losses disproportionately affect smallholder farmers due to inadequate infrastructure and storage facilities. To address this issue, the agricultural industry is increasingly adopting innovative technologies, including nanotechnology, to enhance crop yields and minimize post-harvest losses. Such advancements offer the potential to significantly reduce food waste, increase food availability, and improve the livelihoods of farmers and consumers alike. Key strategies aimed at preserving the quality of fresh produce and extending its shelf life (F&V) include Modified Atmosphere Packaging (MAP), ethylene management, irradiation, heat treatment, edible coatings, and some biotechnological approaches. Moving beyond these practices, another promising avenue for extending fruit and vegetable shelf

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life is by preserving the structural integrity through the inhibition of crucial enzymes involved in the cell wall and plasma membrane breakdown.

Phospholipase D inhibition technology

The cell wall as well as plasma membrane of fruits and vegetables undergo significant degradation during ripening and senescence. These developmental stages, marked by changes in the produce's characteristics, are accelerated by environmental factors like reduced light and temperature, which stimulate ethylene production. At the cellular level, this process involves the breakdown of cellular structures, particularly the plasma membrane which is a dynamic structure composed primarily of phospholipids, sterols, and ceramide monohexosides. To maintain its integrity, the membrane undergoes constant renewal. However, during ripening and senescence, a series of enzymes, particularly phospholipase D, degrade phospholipids that alters the membrane's physical properties, leading to decreased fluidity, increased rigidity, and structural instability. The accumulation of lipid breakdown products further compromises membrane function, ultimately contributing to the deterioration of fruit and vegetable quality(Paliyath & Subramanian, 2008).

Phospholipase D (PLD) is a vital enzyme catalyzing phospholipid hydrolysis via a two-step ping-pong mechanism involving its conserved HKD motifs. This process generates a phosphatidate-PLD intermediate, which subsequently reacts with water or a primary alcohol to produce phosphatidic acid or phosphatidyl alcohol, respectively. The accumulation of these lipid-derived products destabilizes cellular membranes. Optimal PLD activity is under the influence of factors such as acidic pH and calcium ions. Inhibition of PLD effectively attenuates the downstream enzymatic cascade, preventing lipid accumulation and preserving membrane integrity. Hexanal, a 6 carbon aldehyde, has been identified as an effective PLD inhibitor (Paliyath et al., 1999). It is hypothesized that hexanal binds to the PLD active site, mimicking an incomplete transphosphatidylation reaction and consequently inhibiting enzyme activity. This reduction in phosphatidic acid production is postulated to influence ethylene signaling, thereby modulating gene expression associated with fruit ripening and senescence.

Hexanal offers several advantages as a potential postharvest treatment compared to existing compounds used in the preservation of fruits. Unlike broad-spectrum inhibitors such as 1-MCP, which suppress gene expression globally, hexanal demonstrates a more targeted inhibitory effect on ripening-related genes. Furthermore, hexanal's rapid metabolic fate, involving conversion to hexanol followed by oxidation, prevents its accumulation in plant tissues, mitigating potential toxicity concerns (Cheema et al., 2018). While hexanal is naturally biosynthesized in a variety of fruits, its endogenous levels are typically insufficient to induce significant physiological effects. This limitation arises from factors such as low hexanal concentration, compartmentalization within plant tissues, and temporal or spatial separation of its biosynthesis from target processes. Furthermore, the compound's high volatility, a consequence of its low vapor pressure, poses challenges for its practical application in postharvest technologies. To effectively harness the potential of hexanal as a ripening inhibitor, the development of controlled release systems capable of delivering precise and sustained hexanal concentrations is imperative.

Shelf-life enhancement of fresh produce using hexanal

Hexanal-based technologies, targeting phospholipase D (PLD) inhibition, offer a promising approach to extending the shelf life of horticultural produce. Both pre- and post-harvest applications of hexanal can be employed. As a pre-harvest strategy, hexanal is typically applied as a foliar spray to enhance fruit retention and maintain quality prior to harvest. Post-harvest treatments involve immersing the produce in hexanal solutions or exposing it to hexanal vapor to retard spoilage during storage and transportation.

Spray treatment: Hexanal's high volatility necessitated the development of enhanced freshness formulations (EFFs) for effective application as a preharvest spray treatment. EFF1 comprises ethanol, hexanal, and Tween 20, while EFF2 includes hexanal, geraniol, α-tocopherol, ascorbic acid, and Tween 20 in ethanol. These formulations are diluted and stirred to form nano-micelles, enhancing hexanal stability and distribution. The resulting solution is sprayed onto fruits as a fine mist, optimizing coverage. Extensive field trials across various fruits and climates have demonstrated the efficacy of EFFs in significantly extending postharvest shelf life compared to untreated controls. Fruits sprayed with EFF showed improvement in the fruit retention, color retention, enhanced fruit quality, reduced disease and pest incidence which over all contributed to the freshness of fruits(Anusuya et al., 2016; Kumar et al., 2018; DeBrouwer et al., 2020). Preharvest application of hexanal as EFF in sweet cherries retained a brighter red color and show delayed ripening, indicated by upregulated carotenoid biosynthesis and a lower hue angle compared to controls. Similarly, EFF impacts biochemical profiles in other fruits, such as strawberries, where it alters phenolic and volatile compound levels. In greenhouse tomatoes and guavas, EFF improves firmness, increases ascorbic acid and soluble solids, and reduces decay. Preharvest EFF application on mangoes, apples, oranges, and bananas extends fruit retention and reduces diseases, enhancing overall shelf life and quality. Research confirms EFF as a versatile tool for prolonging harvest periods and enhancing postharvest fruit quality, with benefits varying by fruit cultivar. The specific impacts vary by fruit type but generally include better fruit retention, reduced disease incidence, and enhanced biochemical profiles.

Dip treatment: Post harvest application of hexanal as a dip treatment has emerged as a promising technology to prolong the shelf life of a variety of fruits and vegetables. This technique

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involves a brief immersion of optimally mature produce in an aqueous hexanal solution, followed by appropriate storage conditions. Research has demonstrated that hexanal effectively inhibits key physiological processes associated with ripening and senescence, such as ethylene production and phospholipase D activity. Concurrently, it enhances antioxidant capacity, thereby preserving fruit quality attributes like firmness, color, and overall sensory appeal. Successful applications of hexanal dip treatment have been reported for tomatoes, mangoes, papaya, and bananas, among others(Hutchinson et al., 2018; Tiwari & Paliyath, 2011; Yumbya et al., 2018). Consistent findings across these studies highlight the potential of hexanal as a versatile tool for maintaining fresh produce quality and reducing post-harvest losses. While further research is warranted to optimize treatment parameters for specific commodities, the available evidence strongly supports the efficacy of hexanal dip treatment as a valuable component of comprehensive postharvest management strategies.

Vapor treatment: Postharvest application of hexanal as a vapor treatment represents a promising strategy for extending the shelf life of fresh produce. This technique involves exposing fruits and vegetables to hexanal vapor within a controlled environment. Research has indicated that hexanal vapor effectively inhibits microbial growth, delays ripening processes, and can even enhance sensory attributes. While the direct application of hexanal vapor has shown potential, challenges such as high vapor concentration requirements and rapid dissipation have limited its practical application. To overcome these limitations, innovative delivery systems have been developed. Nanofiber and nanopellet formulations have demonstrated the ability to encapsulate hexanal and release it in a controlled manner, thereby prolonging treatment efficacy. These advanced delivery systems have shown success in extending the shelf life of various fruits, including peaches and mangoes (Ranjan et al., 2020, Jan et al., 2022). Continued research and development are necessary to optimize hexanal vapor treatment and its delivery systems for commercial application. This technology offers the potential to significantly reduce post-harvest losses and improve the quality of fresh produce.

Conclusion:

Hexanal has emerged as a promising natural compound with the potential to revolutionize post-harvest fruit and vegetable preservation. Its efficacy in extending shelf life and maintaining quality has been demonstrated across a wide range of crops, including apples, bananas, blueberries, cherries, citrus fruits, grapes, guava, mango, nectarines, papaya, peaches, sweet bell peppers, and tomatoes. Both pre-harvest and post-harvest applications of hexanal have shown positive results. Pre-harvest sprays can help prevent diseases, reducing the reliance on chemical fungicides and pesticides. Post-harvest treatments, such as dips and vaporization, have been effective in delaying ripening, inhibiting microbial growth, and preserving fruit firmness and

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overall quality. While the potential benefits of hexanal are significant, further research is essential to optimize its application and facilitate widespread adoption by farmers. By understanding the underlying mechanisms of hexanal's action and developing innovative delivery methods, such as nanotechnology-based formulations, the full potential of this natural compound can be realized. The agricultural industry is undergoing a transformation driven by technological advancements and a growing emphasis on sustainable practices. Hexanal, in conjunction with other emerging technologies like nanomaterials and precision farming, offers a promising avenue for improving post-harvest management, reducing food waste, and ensuring the delivery of high-quality fresh produce to consumers worldwide. Ultimately, the successful integration of hexanal into post-harvest practices can contribute to a more sustainable and efficient food supply chain, benefiting both farmers and consumers.

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