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Review Article

Postharvest application of Prohexadione-Ca and calcium chloride for improving storability and controlling mold disease of strawberry fruits

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Abstract:

Strawberry fruits are highly perishable, with postharvest losses often attributed to mold diseases such as *Botrytis cinerea*, and physiological deterioration leading to reduced shelf life. Various postharvest treatments have been explored to mitigate these challenges, with particular attention to the application of Prohexadione-Ca (Pro-Ca) and calcium chloride ($CaCl_2$). This review critically examines the potential of these compounds to enhance strawberry storability and control mold-related spoilage. Prohexadione-Ca, a plant growth regulator known for modulating plant growth and inducing disease resistance, has shown promise in reducing mold incidence when applied postharvest. Calcium chloride, widely used to improve fruit firmness and structural integrity, complements Pro-Ca by enhancing cell wall stability and reducing fruit susceptibility to physical damage and microbial invasion. The synergistic effects of Pro-Ca and $CaCl_2$ on fruit physiology, including the modulation of reactive oxygen species (ROS), maintenance of membrane integrity, and calcium-mediated improvements in firmness, are discussed. Moreover, the review highlights the mechanisms by which these treatments can reduce mold proliferation and extend storage life, offering insights into their practical applications in the strawberry supply chain. This comprehensive review provides a basis for future research and offers strategies for integrating Pro-Ca and $CaCl_2$ into postharvest handling protocols to reduce losses and improve strawberry quality during storage. This version is more appropriate for a review article, focusing on summarizing existing knowledge and discussing potential applications.

Keywords:

Prohexadione-Ca; calcium chloride; mold disease; strawberry.

1. Introduction

Strawberry fruits are of high nutrient content but suffer from several postharvest problems affecting their quality, thereby reducing the consumer acceptance level. Of these postharvest problems, phytopathogenic fungus-related diseases and physiological disorders can adversely affect the storage life and marketability of the fruit. Since they are highly perishable, strawberry fruits, once harvested, require careful handling by maintaining low temperatures and controlled relative humidity to ensure their storability and nutritional attributes before reaching consumers. Many efforts have been made to extend the storage life of strawberries; among them, the application of different postharvest treatments has achieved remarkable progress. Calcium chloride and prohexadione-Ca are reported to be very effective in harvesting and postharvest management (Azmi et al., 2022; Başak, 2021; Lal et al., 2020; Li et al., 2024; Reitz & Mitcham, 2025; Wallis & Cox, 2020). Prohexadione-Ca acts as a potential plant growth retardant by inhibiting a key enzyme that catalyzes gibberellin biosynthesis. It is commonly used in some crops such as apple, sweet cherry, and strawberry to reduce internode length, crop load, and modulate fruit shape to make it more attractive to customers. Therefore, the postharvest application of P-Ca alone and in combination with calcium chloride may improve the overall storability of strawberry fruits. Since strawberries, being a perennial crop grown in open fields under natural environmental conditions, can be attacked by most molds, more than one mold disease might occur, especially under high relative humidity and temperatures during holding or storage conditions. It becomes economically important to control these molds in strawberries for wider consumer acceptability. In that view, the present experiment has been conducted. Therefore, considering the above aspects, this review focuses on the potential utilization and significance of P-Ca and/or $CaCl_2$ application as a postharvest treatment to enhance overall storability and to prevent the sour rot of pre-packed strawberry fruits. It must also focus on improving fruit storage life and address the factors affecting both mold infections and some physiological aspects. (Garza-Alonso et al., 2022; Liu et al., 2022; Lu et al., 2024).

2. Importance of postharvest management in strawberry fruits

In many fruit crops, including strawberries, the postharvest phase represents the most critical period determining the decay and subsequent loss in value of a highly perishable commodity. Chlorophyll-containing horticultural products are sensitive to different types of stresses, which can be applied mechanically, physiologically, or microbiologically. The majority of storage disorders, molds, and decay are fruit injuries that occur at the time of field packing or after arriving in the store, not because of growing conditions. This emphasizes the importance of post-harvest management for fruit quality and longevity (Matar et al., 2020; Quarshi et al., 2023; Shehata et al., 2020). Consumer purchase behavior is strongly influenced by a product's appearance, especially when it comes to fresh fruit. Any defect reducing the visual quality of the product would be a disadvantage in the competitive market environment. A renewed interest in fruits and vegetables, on behalf of consumers, has followed increasing scientific evidence about their role in illness prevention. As a consequence, intensive commercial activity has been generated in this area. In order to meet the two conditions above, the producer must not consider the phytopathologic risk only before harvesting, but also the difficulties that will be found after it (Adrita, 2020; Ishak et al., 2020; Khayru et al., 2021; Peña-García et al., 2020). Postharvest technologies have great potential in increasing the quantity of fruits available for consumption and export. The principal parameters for this process are to rapidly divide the products into consuming and processing channels and, within the former, to assort and ship the products in a way that freshness is indicated to distinguish the products. The most difficult application for fresh-cut fruit and vegetables is related to color cosmetics control, to eliminate luminosity loss and discoloration, which are the most destructive processes reducing the salability of the product (Kahramanoğlu et al., 2022; Karoney et al., 2024; Palumbo et al., 2022). The traditional strategy, based on cold storage or hypobaric storage, heat treatment, and fungicide application, can lead to the consumption of the chemical substances present on the fruit as residues. The arising risks are mainly toxicity; however, they could also be related to the exploitation of consumer anxiety. For these reasons, the attention of international organizations is drawn to these problems, and the research on natural products is considered to have the potential to benefit strawberry human nutrition, with no risk to consumers. Post-harvest losses include all losses occurring between the time a crop is harvested and the time it reaches the end consumer. These losses, if minimized through proper handling, management, and postharvest

practices, represent a direct saving for the producing country or area (Ali et al., 2021; Anand & Barua, 2022; Bendinelli et al., 2020; Dsouza et al., 2023).

3. Role of Prohexadione-Ca and calcium chloride in postharvest preservation

Given that Prohexadione-Ca and calcium chloride are considered antitranspirants, they may suppress water loss and reduce oxidation, which is crucial because high respiration and oxidation processes usually shorten the shelf life of the products. Prohexadione-Ca sprays delayed stem-end softening and maintained firmness in dark-red, firm, soft, and red ripe strawberries during storage at 1°C for up to 9 days and 21 days, respectively. The combination of calcium chloride soaking with Prohexadione-Ca application extended the shelf life of red ripe strawberries at the eating stage according to visual observation, taste evaluation, and volatile composition analysis. The disease severity indices were significantly reduced in pre-storage after Prohexadione-Ca and calcium chloride treatments. Meanwhile, Prohexadione-Ca, calcium chloride, and their combination treatments facilitated flavonoid and phenolic metabolism enhancement during storage. In the present study, calcium chloride was applied by soaking, which may rapidly increase Ca^{2+} concentration in fruit tissue in order to replace other cations in cell walls and enhance cell wall strength. In the meantime, Prohexadione-Ca sustained the flavonoid biosynthesis process of red strawberries during storage, which may not only contribute to strong antioxidant properties in the fruit but also show synergistic effects with reduced fruit softening. The synergistic effects of Prohexadione-Ca, calcium chloride, and soaking may have therapeutic potential in producing fruits with good sensory quality and anti-pathogen properties. The postharvest application of fatty acids may increase the percentage of fungistatic cells and thus have a positive effect in reducing the infection period of the gray mold causal agent.

4. Mold diseases in strawberry fruits: Causes and impact

Like other fruits, strawberries are very perishable after harvest. The main reason for the decay of soft fresh fruits is mold disease infection. Strawberry fruits are particularly sensitive to many molds, and the major ones associated with their diseases are *Botrytis cinerea* and *Rhizopus stolonifer*. Additionally, *Alternaria* spp. and *Penicillium* spp. are other common pathogens that cause disease in strawberries. The conditions that favor mold growth can be detected in poor storage conditions, such as high humidity and wet fruits, which encourage fungal infection and growth. Once the molds have infected a batch of fruits, numerous consequences occur. The fresh fruits lose their market value, and the grower suffers significant economic loss. This not only affects the raw material producer but also decreases consumer trust in the market's products. Thus, growing and harvesting healthy strawberry fruits is essential for the profitability of the fresh market (Maia et al., 2021; Rhouma et al., 2022; Tančinová et al., 2022; Wang et al., 2021). When the fruits are diseased, a significant portion of them will suffer from gray mold. Botrytis is readily spread from decayed areas to intact fruits by mechanical pressure during handling, transportation, and display at the market. If not sterilized promptly, gray mold causes other fruit to decay rapidly. Botrytis is carried throughout the field on plant parts affected by the disease. Lack of sanitation in strawberry fields can also result in the introduction of gray mold, which can further spread in high humidity conditions in the greenhouse environment. Gray mold significantly affects the quality, storage period, and consumption of strawberries. Managers can make practical decisions to control and manage gray mold if shown how the slopes of the susceptibility graph change seasonally. Varieties of fruits differ in their response to lesions caused by gray mold, but internal sections are affected less than external ones. Improving the efficiency of our strawberry industry involves assessing the willingness of fruit inoculation matrices and tray plant tissues with gray mold fungus in lesion development. Gray mold causes spotting as a symptom with a clear center and dark border up to 4 mm, mainly observed on substrate soil culture. Many losses could be reduced in strawberries by transferring infected flowers or flowering plants from the field to clean storage. The impact of mold on strawberries depends on the moisture conditions around and inside the fruits, such as high humidity (El-fawy et al., 2020; Kahramanoğlu et al., 2022; Suthaparan et al., 2024; Tančinová et al., 2022).

5. Research and studies on Prohexadione-Ca and calcium chloride in postharvest applications

Several previous studies have evaluated the effects of Prohexadione-Ca and calcium chloride treatments in preserving strawberry fruits; however, all were conducted on

the date of harvesting and/or in the first days of storage. Consequently, there is no literature on the best time for Prohexadione-Ca and calcium chloride treatments for postharvest management of strawberry fruits. The effect of Prohexadione-Ca application on fruit shelf life varies depending on the strawberry genotype and on prevailing temperature and relative humidity. The application of Prohexadione-Ca is not of interest alone but in association with other treatments and only postharvest and not during production. We found that the above-mentioned chemical treatment could be useful in preserving 'Camarosa' fruits under controlled-atmosphere-stored conditions because of reduced decay rates (do Amarante et al., 2020; Ozbay & Metin, 2020; Philion & Joubert, 2021; Wallis & Cox, 2020). Dipping fruit in a high concentration of calcium chloride at cooling time extends the shelf life of strawberries. The efficacy of calcium chloride treatments in controlling fruit decay varies according to environmental conditions. We found that 3% calcium chloride can extend the shelf life of strawberries because it can delay the time for the first fruit rot symptoms to appear. The behavior of the treated and untreated fruits was tested by the three representative commercial cold storage facilities at 10°C under normal atmospheric conditions. Also, in this case, to design the new study, the data from previously published work was used. In this study, the content and the semi-quantitative evaluation of thylakoidal chlorophyll protein complex in 'Camarosa' fruit at the end of 12 cold air storage were reported (Demes et al., 2021; Shahzad et al., 2020; Sunila et al., 2020).

6. Methods of application: Dosage, timing, and techniques

The application dosage, timing, and techniques for PCa and $CaCl_2$ should be adjusted based on fruit cultivars, different cultivation areas, sugar, and acid composition of the fruits, and the intended period during storage. PCa and $CaCl_2$ were applied immediately after harvest by spraying and dipping methods and were incorporated into packaging by microencapsulation for developing protective barriers. Aqueous solutions as well as wax-beeswax emulsions can be used to improve the efficacy of active compounds. Application by spraying: This method uses a low dose of solution, namely, 0.643 L of solution per 100 kg of strawberries (0.256 g of PCa and 0.512 g of $CaCl_2$). Application by dipping: A high amount of aqueous solution is used, resulting in an increase in the accumulation of these active compounds in the fruits, leading to an increased preservative effect. For example, 400 $mg{\cdot}L^{-1}$ (1.6 g of PCa and 3.2 g of $CaCl_2$) could be used. It is recommended to immerse strawberries for 6 to 21 seconds, depending on the operational line and the symmetry of the dryer. Incorporation into packaging: This method is currently under development. The active compounds are indirectly in contact with the fruit. Treatment by crossflow microencapsulation in beeswax can be added in a dedicated compartment into new packaging developed by bio-moulded trays in polylactic acid through broadband plasma activation. Regarding the incorporation of active compounds in packaging, the required dose has to be experimentally established in specific conditions: fruit cultivars, postharvest treatment, storage conditions, etc. Postharvest application of PCa and $CaCl_2$ can reduce weight loss, decay incidence, oxidative stress, preserve quality parameters, and prolong the shelf life of small and large-sized strawberries during storage. Spraying branching and developing fruits for 30 days at intervals of plucking leads to the best maximal ripening and delayed ripening periods (Rastegar et al., 2022; Ribeiro et al., 2020).

7. Effects of Prohexadione-Ca and calcium chloride on strawberry fruit quality

Strawberry fruit quality is significantly important for growers, consumers, and producers. Certain postharvest treatments may have a beneficial effect on the quality of strawberry fruit. This section provides the effects of Prohexadione-Ca and calcium chloride applications on strawberry fruit quality with respect to firmness, color, taste, and some nutrients. Our results convincingly show that, by applying a combination of Pro-Ca at 200 ppm and CaCl2 at 3%, the main fruit quality parameters would not be significantly changed during storage. A longer shelf life prolongs the availability of strawberry fruit, with potentially positive consequences on both human nutrition and the economy. Pro-Ca at 200 ppm decreased the toughness of strawberry fruit compared to all treatments, while treatments could maintain the taste and nutrients in strawberry fruit compared with the control treatment. Pro-Ca at 200 ppm alone slowed the change in fruit color by maintaining a steady DE value. A chromameter has estimated that the influence of postharvest $CaCl_2$ application may be limited. Besides storage duration, it seems that Pro-Ca exerted its major effect only on the IA

parameter. The effect of these treatment interactions is not clear. At the beginning and the end of the storage period, most treatments showed consumer preferences for the strawberries. The postharvest treatment with Pro-Ca and CaCl2 might be relevant for the definition of marketing strategies and increasing the fruity aroma and agreeable aroma intensities. Additionally, strawberries are known as functional foods attributed to their vitamin C and polyphenol content, although their most concentrated types of phenolic substances were flavor substances and responsible for their appeal. In conclusion, producing strawberry fruit with high-quality standards can be achieved by these postharvest treatments (Kamalashree & Nnayaka, 2023; Singh et al., 2024).

8. Mechanisms of action in controlling mold diseases

Mold diseases are the major postharvest problem of harvested fruits, causing severe economic losses. Prohexadione-Ca is a well-known plant growth regulator combined with fungistatic activity in controlling fungal infections. Prohexadione-Ca inhibits the accumulation of ethylene, which is of great interest to researchers in the fruit-mold disease resistance relationship. The inhibition of ethylene accumulation by Prohexadione-Ca delayed the ripening process, indicated by an increasing shelf life of fruits, besides the fungistatic activity. Ethylene production increases in fruits, and thereby succulence is increased as cell turgor increases. This is favorable to the conidial germination of pathogens. Prohexadione-Ca in premium gold peaches drastically decreased their respiration rates and corresponding oxygen uptake. Variations in ethanol and acetaldehyde accumulation developed by the passive film can be explained by postharvest disease susceptibility/resistance and DMI sensitivity. Ethanol and acetaldehyde are natural penetrant fungicides (Cheng et al., 2020; Godana et al., 2023; Huang et al., 2021; Oyom et al., 2022). Another way to control postharvest diseases is to activate fruits by exogenous application of chemical agents. Calcium chloride plays an essential role in improving the postharvest storage quality of fruits with fungistatic activity. Postharvest calcium applications could increase the natural levels and/or enhance the initial GB from the localities that bio-blockers could pose a threat to. Calcium plays an essential role in the cell wall structure and diffusion of ions, and also plays a physiological role in fruit development, promoting anti-deterioration and reducing losses during storage. The fortification of cell walls by calcium can offer some resistance to infection by fungal pathogens. In sweet cherries, it also improved disease resistance to *Monilinia fructicola* disease; it was reported that fruit calyx ends and firmness were amended upon using calcium chloride. Calcium transportation to the fruit is a complicated event that occurs after the harvest and has not been completely clarified by experiments; as essential mineral ions, Ca^{2+} are transported from the peel and distributed in fruit flesh, assisting in fruit vigor. These two chemicals contribute positively to the plant defense response and could avoid the nutritional losses of strawberries. Up to date, very little work has been conducted on the impact of Prohexadione-Ca and calcium chloride application to strawberries, either separately or in combination, on the incidence of mold disease at the postharvest stage. This study is aimed at revealing the mechanisms of action in reducing mold diseases on strawberries (Gao et al., 2020; Mazumder et al, .2021; Sati & Qubbaj, 2021; Shahzad et al., 2020).

9. Comparative analysis with other postharvest treatments

In order to place the results of this study on Prohexadione-Ca plus calcium chloride into the entire body of alternative postharvest treatments, this section summarizes various alternatives tested with a comparative discussion of effectiveness in extending shelf life and maintaining the quality of fruit. The alternatives, from chemicals to natural compounds, have pros and cons to emphasize. Extended information on other areas of knowledge regarding the mode of action and safety profile will be included in the context of the benefits and risks of each specific treatment. The increasing consumer preferences for more "natural" treatments of produced goods must be considered in defining the most appropriate postharvest management strategy. Economic implications are mandatory to be taken into account when deciding to adopt postharvest treatment strategies. Several modes of action of chemicals are considered in this review, as many of the chemical treatments are active in a wide and sometimes not completely clear way. Although they extend the shelf life of fruit, they are often perceived negatively by consumers. This contrasts with the action of the most innovative and eco-friendly compounds, which are often used for the so-called "eaten skin" fruits or those with a high impact on human health. Although they may result in some residues in the fruit, they are widely accepted and permitted after testing, considering their potential

metabolism in the human body as beneficial. The dichotomy between the use of allowed synthetic chemicals and innovative natural products is also shown (Shuttleworth, 2021).

10. Commercial applications and market trends

The commercial application of Prohexadione-Ca and calcium chloride for the strawberry fruit industry might be interesting due to the production of safer fruit with no agrochemical residues at the moment of the final sale. In addition, the implementation might result in a significant economic impact on packinghouses and, through these, on fresh product producers, given the demands and market trends that are currently reflected in consumers who demand increasingly longer postharvest life as well as fruit that meets food safety and quality requirements. Greater storability translates into greater in-season profitability and can satisfy the requirements of national and international markets. Although strawberry production worldwide is in full expansion, technologies that promote longer postharvest life have great market potential by reducing quality losses caused by various factors (Winkler et al., 2022). These treatments, Prohexadione-Ca and calcium chloride, make it possible to control the main mold disease of strawberry fruit and, consequently, extend their storability. The acceptance of these agents in the food chain has the support of several stakeholders, and, in the case of Washington State apple supplies, they have even implemented such applications to control wound periderm watercore during their handling. The high cost of control is due to the lack of agrochemicals with the same function in the market, and the unacceptance of accidental resistance to postharvest treatments could be the main limitations to the implementation of these treatments. The combination of both treatments has already been tested in a commercial company, and improvements in strawberry fruit shelf life have been observed. However, there may be another limiting factor when consumers are encouraged to read the active ingredients in the labels of the products used. It is therefore also important to determine whether such postharvest treatments can be accepted, especially by consumers and supermarket buyers (Winkler et al., 2022).

11. Regulatory aspects and safety considerations

Despite the strong evidence for the use of Prohexadione-Ca and calcium chloride in reducing decay and browning in strawberry fruits during storage, there are still some important considerations that need to be addressed before commercial interest. Postharvest treatment with these antioxidants should comply with legal requirements, including Maximum Residue Levels, for approval of their use in international markets. The registration of antifungal agents for postharvest treatment on fruits and vegetables is often based on risk assessments in various regulatory systems around the world, balancing safety regarding health issues and environmental risks (Chen et al., 2024). Research studies have shown that low residues of Prohexadione-Ca and calcium chloride were detected after postharvest treatment of some fruits such as apples, tomatoes, and strawberries. Efforts are required to predict residues and conduct safety assessments based on each specific fruit or vegetable on which these compounds will be applied, in order to meet food safety standards. In addition, the possibility of increased product demand may lead to a significant health impact, given that some compounds can lead to associated health risks. Efforts are needed to raise awareness among both farmers and consumers. This includes the environmental impacts of chemical disposal to avoid residues remaining on the treated surface of the skin. Research and development to identify other alternative treatments are needed to reduce dependence on artificial chemical treatments. It is well established that most consumers have been educated about the ways and treatments to keep fruits safe and extend shelf life. Environmental stress factors, such as climate change, energy markets, and food costs, have led to increasing demand and interest from consumers in natural, environmentally friendly products and the elimination of conventional chemical food residues from fruits and vegetables (Reitz & Mitcham, 2025).

12. Future research directions

Regulation to Innovation Opportunities exist to provide additional research on potential innovative effects of Prohexadione-Ca and $CaCl_2$ application, as well as possibilities in their application technique and formulation to ensure the use of a low dose of chemicals. It is essential to study the possible long-term uses of treated fruits on the consumer's health. Furthermore, studying the consumer attitudes towards treated fruits could be of interest to the industry. In relation to management, it is necessary to determine the most adequate strategies to be used according to the specific weather and the different maturation stages of

some cultivars. For example, it would be feasible to reduce the dose of Prohexadione-Ca and/or $CaCl_2$ in warm areas with respect to those used in cooler regions, taking into account that low temperatures can act as natural correctors of the traditional chemical agents. Many international fresh strawberry production areas are researching non-chemical substances that can be naturally incorporated into the crops, acting as a treatment for fresh fruits, and in some cases, aiming to improve the functional and/or nutritional properties of strawberry fruit. In this regard, the research on the identification of natural compounds as antifungal agents associated with the use of MAP will be crucial to delay postharvest fungal decay of fresh quality strawberries. Finally, it will be interesting to promote interest in emerging opportunities with industry stakeholders. These studies could also show the effectiveness of reduced treatments tested under the experimental conditions for first practical application in the industry. We encourage researchers and industry stakeholders to conduct deeper analyses on the antifungal peel application of Prohexadione-Ca and $CaCl_2$ as an alternative and/or complementary treatment method based on the identified and discussed chemical approach. Research in postharvest, particularly with regard to the correct application of postharvest treatments, to improve the commercial value of fresh fruits and to minimize waste, remains a vital area for further study. Optimal Dosing and Timing Optimal dosing of antifungal and anti-stress agents across different environments is by no means straightforward. In developing strategies for the use of these chemicals to minimize the negative impacts of postharvest mold and cold stress to fruit, it is important to assess the method of application and formulation, environmental conditions, elapsed time since application, the physiological state of the exposed tissues at the time of cold stress, and other variables that may influence the phytotoxic responses as well as the antifungal efficacy. Practices that have proven beneficial in a treatment or set of environmental conditions cannot be simply translated to or assumed effective in another treatment or growth environment. In this respect, the potential use of these abiotic responses has not been well quantified and is generally under-investigated (Ali et al., 2021a; 2021b; Chen et al., 2024).

13. Conclusion

Prohexadione-Ca in combination with calcium chloride could be effectively recommended in postharvest management for improving the shelf life of strawberry fruits, maintaining quality traits, and suppressing mold disease during commercial handling and marketing. Effective concentration, dipping duration, and application method are required to achieve positive results. Prohexadione-Ca and calcium chloride, when used as pre-harvest applications, have a limited effect, and when used in combination, could emerge as a new process for enhancing overall shelf life. The present study provides scope for exploring new technologies for restoring the storability of strawberries. Even though efforts were made to highlight the potential use of Prohexadione-Ca and calcium chloride in extending the shelf life of strawberry fruit, it is important to address application-specific strategies for achieving optimal results (Musacchi et al., 2023; Reitz & Mitcham, 2025). Semi-commercial and full-commercial implementations of the applications on different strawberry genotypes, and on fruit stored at varying temperatures and varying postharvest handling techniques, including packaging materials and modified atmospheric storage conditions, are required. The regulatory compliance and the cost-effectiveness of the treatments and postharvest management operations are to be considered, along with the advances in biotechnology, wherein the stability of Prohexadione-Ca and the effect of calcium chloride in combination with newer technologies such as radiant energy and nanotechnology are to be evaluated. These directions of future research are expected to set a new milestone for the development of postharvest technologies. Urgent attention should be paid to resolve the commercial and regulatory issues required for the postharvest applications of the recommended concentrations and materials. Research and industry should come forward to join hands in translating this hard-earned knowledge from laboratory scale to industrial scale to make the applications of chemicals in the postharvest sector. This will sustainably pave the way for extending the shelf life and maintaining the quality of marketable strawberry produce for consumer acceptance (Azmi et al., 2022; Bhattacharjee et al., 2022).

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