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Effect of pre-harvest sprays of Zn, Ca, and Fe on postharvest aspects of strawberry: A review

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Abstract
Favored for their brilliant color, delicious flavor and high nutritional content, strawberries (*Fragaria* × *ananassa*) are fragile and can quickly deteriorate when handled and stored after harvest. Strawberry, the perishable fruit, is prone to excessive-quality loss due to microbial deterioration and physical injury. Pre-harvest sprays play a crucial role in enhancing the shelf life of strawberry. Nutrient management has come to light as one of the many variables affecting post-harvest quality and can potentially improve fruit quality and increase shelf life. This thorough analysis explores the complex functions that three necessary nutrients iron (Fe), calcium (Ca) and zinc (Zn) have in determining what happens to strawberries after they are harvested. The potential of zinc, calcium and iron (Zn, Ca and Fe) in maximizing the storage conditions and maintaining fruit quality plays an important role. To improve the firmness, disease resistance and shelf life of strawberries it is important to apply pre-harvest nutrient application in a balanced way and also adapt suitable methods depending on particular growing conditions. These nutrients provide a variety of advantages that are carefully considered when developing post-harvest management techniques for strawberries. These benefits range from enhancing the antioxidant defences to strengthening cell walls and reducing pathogen growth. The study aims to provide producers and stakeholders with optimized practical insights to improve post-harvest quality and market competitiveness of the fruit strawberry.

Keywords: Zinc, calcium, iron, pre-harvest sprays, strawberry, quality, physiological character

Introduction
Strawberry is one of the most popular berry fruits of the Rosaceae family, genus Fragaria scientifically known as *Fragaria* × *ananassa* (Fierascu *et al.*, 2020) [21]. Strawberries have always piqued interest of people due to their vivid color, unique scent and mouth-watering taste. It is highly consumed for its rich nutritional content and possible health advantages, in addition to its delicious flavour (Bakshi *et al.*, 2013) [10]. Strawberries have been prized in many civilizations throughout history and have been incorporated into mythology, artwork and culinary customs worldwide (Fierascu *et al.*, 2020) [21].
Strawberries are marketable, satisfy customers and the post-harvest stage is essential to preserving their quality and prolonging their shelf life. Strawberries are incredibly perishable after harvest because of their high water content, sensitivity and vulnerability to microbial deterioration and physical injury (Azam *et al.*, 2019) [8]. Strawberries must be managed well to maintain their nutritional content, freshness and quality. Stakeholders may reduce losses, increase marketability and satisfy consumer demand for premium-grade strawberries across the supply chain by using appropriate pre and post-harvest treatments (Florkowski *et al.*, 2021) [22].
Due to laying the groundwork for fruit growth, physiological maturity and stress tolerance, the pre-harvest stage significantly impacts the post-harvest quality as well as the shelf life of strawberries (Ali, 2012). The possibility of applying vital nutrients, including iron (Fe), calcium (Ca) and zinc (Zn) before harvesting to enhance the quality of strawberries plays an essential role. These micronutrients are necessary for physiological processes, like fruit growth, ripening and stress response. As a result, they affect the characteristics of the fruit after harvest, such as firmness, shelf life, color retention and nutritional content.
The growth of fruit and its quality are impacted by zinc (Zn), which is engaged in processes related to protein synthesis and carbohydrate metabolism (Zewide *et al.*, 2021) [56].

Pre-harvest Zn sprays have been demonstrated to improve the firmness of fruit as well as its shelf life by enhancing cell wall integrity and lowering the fruit's vulnerability to carefully handle the fruit. Zn treatment is also connected to enhancements in fruit taste, color and antioxidant capacity, all of which generally improve post-harvest quality.

The structure and strength of the fruit's cell walls are influenced by calcium (Ca), which also affects the fruit's susceptibility to physiological problems, including softening and bruising (Hussein *et al.*, 2020) [31]. According to reports, pre-harvest Ca sprays raise the calcium content of strawberry fruits, improving cell wall durability, lowering spoilage and post-harvest deterioration. Additionally, applying calcium can reduce the frequency of diseases like blossom-end rot, which enhances the marketability and look of fruit (Glenn, 1987) [25]

Fruit color, flavor and nutritional value are all impacted by iron (Fe), which is necessary for photosynthesis, respiration and chlorophyll production in plants (Zhang *et al.*, 2023) [59]. Pre-harvest Fe sprays have been researched for their ability to boost strawberry fruit color development and anthocyanin accumulation, increasing the fruit's visual attractiveness and customer acceptability. Applying Fe to strawberries may also strengthen their antioxidant defense, increasing their shelf life and maintaining their nutritional content during post-harvest storage (Kazemi, 2014) [33].

Pre-harvest zinc (Zn), calcium (Ca) and iron (Fe) sprays help to improve strawberry quality after harvest and have the potential to enhance shelf life, firmness, color retention and nutritional content by maximizing nutrient availability and physiological processes during fruit development (Panigrahi *et al.*, 2019) [42].

Post-harvest losses in strawberry

In India, losses incurred after harvesting strawberries can be startlingly large, frequently amounting to 30-40 percent of the overall yield. These losses happen throughout the supply chain, including during the harvesting, shipping, storing and selling phases (Surucu and Tuna, 2021) [55]. Strawberries are very sensitive to physical damage, microbiological spoilage and fast senescence due to their perishable nature, greatly increasing postharvest losses.

Many factors cause the substantial postharvest losses of strawberries in India. As strawberries are often gathered by hand, treating them incorrectly can cause bruising and damage. The problem worsens when there are no established techniques for harvesting. Non-refrigerated vehicles are usually used to carry strawberries from farms to markets. Heat exposure and hard handling during transportation fruit degradation can be accelerated. The best conditions for strawberries to be stored are at low temperatures and high humidity (Alcéo and André, 2016) [4]. Unfortunately, a lot of farmers and dealers don't have access to adequate cold storage facilities, which causes food to degrade quickly (Baicu *et al.*, 2018) [9]. The delicate strawberries are not well protected by conventional packing techniques such as utilizing jute bags and bamboo baskets. Contemporary packaging options that reduce damage and increase shelf life are not frequently used. Fungal illnesses such as Botrytis cinerea (gray mold) are particularly common among strawberries many potential microbe infections. Significant microbial deterioration can result from inadequate handling and storage cleanliness as well as poor postharvest hygiene procedures (Azam *et al.*, 2019) [8].

A comprehensive strategy incorporating better harvesting, transportation, storage and packaging techniques is needed to address the postharvest losses of strawberries in India. This loss may be considerably decreased by implementing new infrastructure and technology, improving farmer education and raising farmer awareness. In addition to increasing strawberry farming's profitability, these initiatives will guarantee customers a more consistent supply of this beloved fruit (Feliziani and Romanazzi, 2016) [20].

Types of Pre-harvesting Sprays

Pre-harvesting sprays applied before harvesting are essential elements of contemporary farming methods, intended to improve crop quality, productivity and resilience against pests and illnesses. These sprays include a range of compounds, including growth regulators, insecticides and nutrients which are administered throughout the growth period.

Fruits treated with pre-harvesting sprays have a substantial improvement in their quality, robustness, and durability after harvest (Kasera *et al.*, 2024) [32]. These sprays contain growth regulators, biostimulants, fungicides and nutrients, each of which has advantages of its own. Fruit degradation is reduced when nutrient sprays guarantee that fruits develop with the best possible nutritional content and structural integrity. Fungicides lower the danger of spoiling after harvest by preventing disease (Khan *et al.*, 2018) [34]. Fruits with improved size, color and firmness due to the use of growth regulators and biostimulants are more resilient to handling damage. Furthermore, certain sprays postpone ripening and senescence, giving storage and transit additional time. Fruits are better able to tolerate changes in their environment because biostimulants increase their stress tolerance (Afonso *et al.*, 2022) [1]. Fruits that retain their quality, freshness and nutritional content for extended periods are the outcome of these combined impacts, which eventually lower post-harvest losses and boost marketability (Khan and Ali, 2018) [34]

Nutrient sprays are crucial to providing plants with the ingredients they need to thrive to their full potential. Trace elements including zinc, iron, manganese and boron which are essential for plant metabolism and development are provided by micronutrient sprays. Reduced production and stunted development can be caused by deficiencies in certain micronutrients. Plants that get macronutrient sprays of nitrogen, phosphorus and potassium are guaranteed to obtain the essential nutrients required for photosynthesis, root growth and general health. By preventing excessive vegetative development, anti-gibberellins improve fruit setting and raise the yield that can be harvested (Preininger *et al.*, 2018) [45].

Pre-harvest sprays have several advantages. They supply the right nutrients and hormone balance, they dramatically increase production and quality in plants. Pre-harvesting sprays also have the important advantage of efficiently using nutrients. Sprays that target specific shortages in nutrients especially micronutrients ensure that plants use resources effectively and minimize waste. With this focused strategy, crop output is maximized and environmental effect is minimized.

To sum up, pre-harvest sprays are essential to contemporary agriculture and provide a host of advantages, including better yield and quality as well as better control over pests and diseases. With so many sprays on the market, farmers may tailor their methods to the unique requirements of their crops, guaranteeing maximum yield and sustainability. Farmers may improve quality, productivity and environmental stewardship by incorporating these sprays into their farming techniques (Patil *et al.*, 2023) [43].

Time and method of application of pre-harvesting sprays

Pre-harvest micronutrient spraying strawberries is a crucial agronomic technique meant to increase fruit yield and quality. In this method, micronutrient solutions are strategically applied at particular growth stages, mainly during the flowering and fruit set periods (Kuchi *et al.*, 2019) [36]. The plant needs more nutrients during flowering to support the growth of flowers and later fruit. At this point, spraying micronutrients like calcium, zinc, iron, manganese and boron can help support the early stages of fruit production, increase pollen viability and improve pollination. Iron is necessary for the synthesis of chlorophyll and photosynthesis, while zinc is vital for activating enzymes and synthesizing proteins. Calcium is essential in maintaining the integrity and structure of the cell wall, this improves the fruit's resistance to deterioration and its structural integrity (Suman *et al.*, 2017) [54]. During the colder hours of the day, a fine mist sprayer should be used to provide the nutrients ideally in chelated forms for improved absorption to guarantee optimal uptake. Proper harvesting techniques and post-application monitoring help to guarantee that strawberries retain their freshness and quality throughout storage (Meena *et al.*, 2025) [40].

The continuous administration of these micronutrients helps to prevent deficits that could impair fruit development and quality as the fruit sets and starts to develop (Ganeshamurthy *et al.*, 2018) [23]. During this time, optimum cell division and growth are supported by sufficient nutritional availability, which results in larger, more evenly grown strawberries. Strengthening the general health and resilience of the plant, these micronutrients can enhance the fruit's color, flavor and shelf life (Bakshi *et al.*, 2013) [10].

Effect of varying concentration of minerals on strawberry

Mineral nutrients play a crucial role in influencing the growth, development, and fruit quality of strawberry plants. Varying concentrations of nutrients can significantly affect physiological processes such as photosynthesis, nutrient uptake, flowering, and fruit formation. Optimizing mineral concentrations is essential to achieve high yield, superior fruit quality, and improved stress tolerance in strawberry cultivation as shown in Table 1.

Table 1: Concentration of mineral nutrition used an observation made in previous years

S. No.	Mineral nutrition	Treatment	Observation	Cultivars/ Varieties	References
1.	$ZnSO_4$	150 mg /l	The highest percentage of TSS, titratable acidity, plant yield, and ascorbic acid was attained in fruits.	Pajaro	M.Kazemi, 2014 [33]
2.	Fe	1000 mg/l	Increase plant yield	Pajaro	M.Kazemi, 2014 [33]
3.	Ca	10 Nm	Increase plant yield	Pajaro	M.Kazemi, 2014 [33]
4.	$FeSO_4$	0.6%	Increases sugar content of fruit	Chandler	Bakshi *et al.*, 2013 [10]
5.	$ZnSO_4$	0.6%	Maximizes ascorbic acid and anthocyanin	Chandler	Bakshi *et al.*, 2013 [10]
6.	$CaCl_2$	0.6%	Extends the shelf life of strawberry	Chandler	Bakshi *et al.*, 2013 [10]
7.	$CaCl_2$	0.4%	Less infestation of albinism and grey mould followed by high ascorbic acid and acidity.	Chandler	Singh *et al.*, 2007 [52]
8.	Ca:B: Zn	1:0.25:1 g	Highest acidity in red Merlin as compared to others	Red Merlin, Elyana, and Fortuna	El-Hefnavi *et al.*, 2021 [18]
9.	Ca:B: Zn	2:0.75:2 g	Highest fruit content of TSS, non-reducing sugar, reducing sugar and total sugar	Red merlin, Elyana, and Fortuna	El-Hefnavi *et al.*, 2021 [18]

Effects of Pre-Harvest Spray of Zinc (Zn)

An essential micronutrient, zinc (Zn), is involved in various enzymatic activities and plant metabolic processes. Some have looked into the possibility of using pre-harvest zinc sprays to increase the firmness, color development and antioxidant capability of strawberries after harvest (Bakshi *et al.*, 2013) [10]. Research has indicated that administering zinc helps alleviate physiological issues after harvest, such as softening and decay, by strengthening cell walls and decreasing oxidative stress as shown in Fig 1 (Guo *et al.*, 2023) [26]. Zn-treated strawberries have improved taste, acidity and sugar build-up, increasing their marketability and general customer approval.

Zinc is also necessary for activating enzymes in creating cell walls and the metabolism of carbohydrates (Brown *et al.*, 1993 and Said *et al.*, 2009) [12, 49]. This guarantees appropriate ripening and firmness of the fruit, two essential aspects influencing its shelf life after harvest. Zinc helps prevent mechanical damage during harvesting and subsequent handling by fortifying cell walls, which lessens the likelihood of bruising and decay (Solanki, 2021) [53].

Zinc also helps fruits become firmer, which is important for maintaining structural integrity and reducing post-harvest losses. The production and cross-linking of cellulose, hemicellulose and pectin components of cell walls require zinc ions (Zhang *et al.*, 2024) [58]. Because these structural polymers give cell walls strength and stiffness, fruit is firmer and more resistant to mechanical damage during handling and transit (Hussein *et al.*, 2020) [31].

Applying $ZnSO_4$ has the best effect on TSS content in fruit and it also has an impact on enzymatic activities, as well as enzymes that mobilize the carbon compound to glucose, lessening the acidic content. Using $ZnSO_4$ maximizes ascorbic acid and anthocyanin and it is due to its function in the biosynthesis of chlorophyll (Salman *et al.*, 2023) [50].

Zinc is a vital element that is involved in several biochemical activities that are important to regulate growth as well as development. Zinc is essential for photosynthesis, enzyme activation and hormone control in strawberries. These processes immediately affect the quality of the strawberry fruit (Solanki, 2021) [53]. Zinc is physiologically involved in the synthesis of auxins, which are plant hormones that promote cell elongation and division. Sufficient zinc levels encourage robust fruit growth, resulting in bigger, firmer strawberries with better taste and color. Zinc also contributes to the production of pigments such as chlorophyll, which improves the fruit's appearance (Sharifan *et al.*, 2021) [51]

Zinc supplementation is essential for improving the nutritional profile and post-harvest quality of strawberries. Its contribution to antioxidant capacity, which is essential for increasing shelf life, is one important feature (Aminzade *et al.*, 2024). Antioxidant enzymes like peroxidase (POD), catalase (CAT) and superoxide dismutase (SOD) all work better when zinc is present because together, they scavenge reactive oxygen species (ROS) that cause oxidative stress. Zinc inhibits oxidative damage to lipids, proteins, and nucleic acids in cells, which helps postpone senescence and preserve fruit freshness in storage.

Zinc spray's effects on strawberries after harvest highlight the fruit's potential as a viable intervention to improve fruit quality, extend shelf life and reduce post-harvest losses. These findings suggest sustainable techniques to maximize fruit production and supply chain management, with substantial implications for the agriculture sector (Asgarian *et al.*, 2024) [7].

Effects of Pre-Harvest Spray of Calcium (Ca)

Fruit firmness, texture and resistance to mechanical damage are all influenced by calcium (Ca), which is essential for maintaining the integrity and structure of the cell wall. Pre-harvest calcium sprays have been studied as a means of boosting calcium absorption and deposition in fruit tissues, therefore increasing the quality of strawberries after harvest as shown in table 1 (Kazemi, 2014) [33]. It is seen that strawberries treated with calcium (Ca) are less prone to bruising, softening and rotting while stored because of their stronger cell walls and improved membrane stability (Chandrakar *et al.*, 2018) [13].

Pre-harvest calcium spray affects several physiological functions in strawberries after harvest. Calcium helps in maintaining membrane integrity, which is essential for the overall structural stability of the fruit (Barman *et al.*, 2018) [11]. By stabilizing membranes, calcium reduces electrolyte leakage, a common indicator of cellular damage, thus preserving fruit quality. Moreover, calcium is essential for signal transduction pathways, controlling the expression of genes linked to pathogen defense systems and stress reactions (Zhang *et al.*, 2014) [58]. The fruit is better able to tolerate environmental challenges during post-harvest handling and storage because of this gene expression modification.

Additionally, fruit color, taste and shelf life have all been linked to improvements with Ca application, which raises consumer satisfaction and increases marketability. Application of $CaCl_2$ maximizes crude protein. Strawberries have an extended shelf life when $CaCl_2$ is applied as shown in fig 1. Fruit shelf life is influenced by various factors, including firmness and water-soluble pectin. Ca has a crucial function in preserving the structure of the cell walls of fruits, combining with the pectin acids to generate pectate, which improves fruit firmness. (Poovaiah, 1986) [57].

Because of application of calcium enrichment affects cell wall integrity and texture maintenance, it has become clear that this is a crucial technique for improving strawberry texture and shelf life (Hernandez *et al.*, 2008) [28]. By creating cross-links between pectic polysaccharides, calcium plays a critical function in maintaining cell wall structures and improving the stiffness and strength of cell walls. The harder fruit firmness that results from this cell wall strengthening is preferable for preserving fruit integrity during handling and storage after harvest (Lara *et al.*, 2019) [38]. Furthermore, the management of ion channels and membrane permeability is made easier by calcium ions. This helps to maintain cell turgor pressure and prevent cellular collapse, which in turn preserves fruit texture and lessens its vulnerability to mechanical injury.

Supplementing strawberries with calcium efficiently lowers post-harvest deterioration and increases disease resistance (Pandey and Srestha, 2023) [41]. As a signaling molecule, calcium initiates the production of antimicrobial chemicals and sets off defensive mechanisms against infections. Calcium fortifies fruit defense systems by strengthening cell walls and triggering the activation of genes associated with defense, making the fruit more resistant to bacteria that cause decay and fungal infections (Martins *et al.*, 2021) [39]. In addition to increasing the shelf life of strawberries, this decrease in post-harvest decay also reduces losses that occur during storage and transit, increasing the total marketable output and producer profitability.

Calcium works as an agent to middle lamella protein-pectin complexes that are stabilized by intermolecular binding (Dey and Brinson 1984) [16] and, thus is crucial for preserving the integrity of cell walls. It is well known that calcium slows down the physiological processes that solubilize and depolymerize pectin and other cell wall polymers naturally, including respiration, ripening and senescence (Agar *et al.*, 1999; Rosen and Kader 1989) [2, 47]. Consequently, the rate at which soluble pectin fractions rise is slowed down as a result of physiological processes that take longer to complete. It appears that calcification and radiation have significantly slowed down the natural process of turning insoluble pectin into soluble form during storage. Due to the synergistic impact of calcium absorption into the cell wall and the subsequent delay of ripening and enzymatic activity, water-soluble pectin levels are lower when exposed to Ca and gamma radiation. This maintains the lowest amounts of water-soluble pectin by slowing the rate at which insoluble pectin converts to soluble pectin (Hussain *et al.*, 2023) [50].

The physiological, biochemical and cellular processes of post-harvest strawberries are impacted in a variety of ways by the administration of calcium pre-spray. Increased structural integrity, delayed ripening, texture preservation and improved nutritional quality make calcium pre-spray an effective technique in the post-harvest supply chain for increasing strawberry shelf life and marketability (Asgarian *et al.*, 2024) [7].

Effects of Pre-Harvest Spray of Iron (Fe):

For several physiological functions in plants, such as photosynthesis, respiratory metabolism and chlorophyll production, iron (Fe) is necessary. Pre-harvest Fe sprays have been investigated for their ability to affect fruit color, antioxidant capacity and nutritional content, perhaps improving the quality of strawberries after harvest as shown in fig 1. According to studies, strawberries treated with iron (Fe) have increased anthocyanin accumulation which results in a striking color and aesthetic appeal (Bakshi *et al.*, 2013) [10]. Furthermore, applying Fe may strengthen strawberries' antioxidant defenses, preventing post-harvest deterioration and increasing shelf life. To optimize Fe treatment rates and timing and maximize favorable effects on strawberry quality while avoiding possible phytotoxicity, more studies are necessary (Kumar, 2017) [37].

The application of $FeSO_4$ gave the best growth out of all the nutrients. The use of $FeSO_4$ increases iron content in plants and it is essential for plant growth. The application of iron increases the availability of water and nutrients resulting in better physiological performance (Eliaspour *et al.*, 2020) [19]. Iron is also utilized to lower Cr stress levels, which are characterized by reduced photosynthetic activity, low stomatal conductance, low water usage efficiency and low plant transpiration rate. Additionally, it has been shown to boost stomatal conductance, transpiration rate, photosynthetic activity and water usage efficiency when chlorophyll concentration is raised (Aliharby and Ali, 2022) [3].

Cytochrome and iron both contribute to the production of chlorophyll and chloroplast RNA metabolism, which produces more biosynthesis materials and accelerates development (Said-Al Ahl and Omer, 2009) [49]. Iron is vital for producing amino acids and enzymes, which enhances the activity of antioxidant enzymes and cell division (Khazaal, 2023) [35]

Sugars, organic acids and phenolic compounds are just a few of the substances in strawberries that iron affects during synthesis and metabolism (Saavedra *et al.*, 2022) [48]. These substances enhance the fruit's taste, fragrance and nutritional content. Strawberries that have been pre-sprayed with iron are more likely to accumulate these bioactive chemicals, making them sweeter and more delicious with better post-harvest qualities.

Fe raises yield when used as foliar sprays during full bloom. The quantity of fruits per plant increased in tandem with the production gains that were found here. The quantity of fruits on a tree was associated with the concentration of chlorophyll in its leaves (Erdal *et al.*, 2004) [17]. Fruit sets are seen to be hampered by iron shortage and Fe-deficient trees have been observed to have a higher proportion of flowers with no ovaries. Because iron is needed to form thylakoid membranes in the chloroplast, low levels of iron in the body result in reduced levels of photosynthesis, electron transport capacity and chlorophyll in leaves. Fruit with $FeSO_4$ applied has a higher sugar content (Davarpanah *et al.*, 2020) [15].

Fe pre-spray's diverse impacts on post-harvest strawberries highlight the product's promise as a viable and efficient method for enhancing fruit quality, prolonging shelf life and lowering post-harvest losses. Fe pre-spray treatment provides a comprehensive strategy for improving the post-harvest performance of strawberries by focusing on physiological, biochemical and cellular processes. This benefits farmers and consumers alike in the agricultural value chain (Erdal *et al.*, 2004) [17].

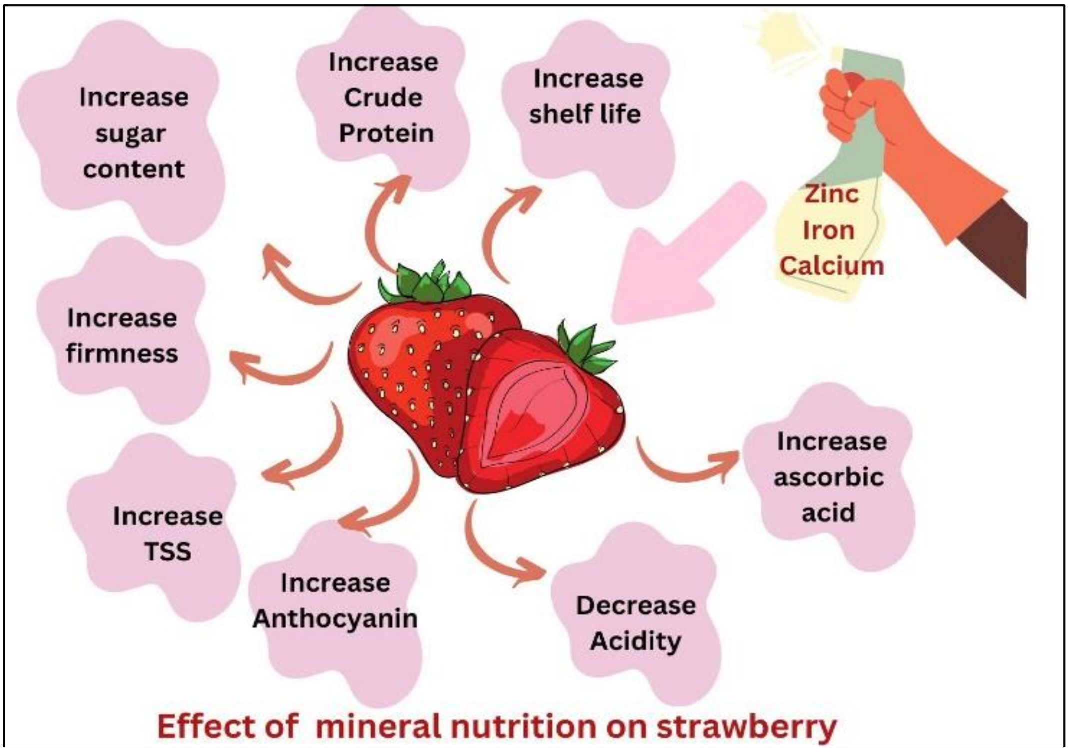

Fig 1: Effect of mineral nutrition on strawberry

Conclusion

There are notable impacts of zinc (Zn), iron (Fe) and calcium (Ca) on the quality of strawberries after harvest. Zinc helps with protein synthesis and enzyme activation by promoting fruit firmness and postponing ripening. On the other hand, too much zinc can be harmful. Chlorophyll production, sugar build-up and fruit colour maintenance depend on iron. Fruit quality may be compromised by photosynthesis being hindered by insufficient Fe levels. By strengthening the structure of the cell walls, calcium keeps the fruit solid and stops it from decaying. Maintaining equilibrium between these nutrients is crucial for preventing negative interactions and enhancing fruit physiology. To maximize post-harvest results, sustainable nutrient management techniques adapted to particular crop requirements are required.

Research has also emphasized the significance of calcium, zinc and iron in controlling physiological functions in strawberries after harvest. For instance, calcium is essential for the integrity of the membrane and the formation of cell walls, whereas iron and zinc are needed for enzymatic processes and antioxidant defense systems. Pre-spraying strawberries with these micronutrients gives them the resources they need to continue their metabolic processes and withstand the stresses of handling and storage.

All things considered, adding Ca, Zn and Fe pre-sprays to strawberry production seems like a good way to improve post-harvest results. Growers, distributors and consumers may all profit directly from these treatments, which improve fruit quality, prolong shelf life and reduce losses. Sustaining the competitiveness of the strawberry business and enhancing post-harvest management procedures need ongoing study and use of such pre-sprays.

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