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Challenges of postharvest water loss in fruits: Mechanisms, influencing factors, and effective control strategies – A comprehensive review

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ABSTRACT

Water loss is a critical concern in postharvest fruit technology, significantly impacting fruit quality, shelf life, and market value. This phenomenon involves the loss of moisture from fruit tissues, leading to physiological changes, reduced quality, and lower market value, which can contribute to food waste. Consumers perceive fruit with visible signs of water loss as lower quality. Therefore, minimizing water loss is essential through proper postharvest handling and storage practices, including temperature and humidity control, cooling, humidification, and the application of edible coatings and new modified coating techniques. Despite the importance of managing water loss, comprehensive information on its mechanisms and contributing factors in postharvest fruit technology is scarce. This paper aims to provide insights into the mechanisms, impact, influencing factors, and control strategies related to water loss in the context of postharvest fruit technology.

1. Introduction

Postharvest water loss, which occurs naturally in fruits through the process of transpiration, presents a significant challenge by diminishing the fruit quality, shelf life, and market value. It was reported that nearly half of fruits at about 45–55 % are lost during postharvest handling and storage [1]. In comparison, cereals, seafood, and meats experience lower losses at approximately 30 %, 35 %, and 20 %, respectively [1–3]. Even at a modest of 3–10 % water loss can negatively impact the fruit texture and render it unmarketable [4]. This problem primarily arises from the fruit's susceptibility to water loss leading to an increased vulnerability to pathogens, flavour and taste changes, and nutrient loss [5–7]. Water loss is also known as weight loss [8,9], and moisture loss [10–12].

Fruits are prone to continuous water loss throughout postharvest processes, including handling, transportation, and storage [13]. Even a minor loss of water can alter their physical characteristics, causing wilting, shrinking, and reduced firmness [14,15]. The level of water loss is critical in determining the freshness of horticultural products, as excessive water loss can significantly impact their market value and consumer acceptance [16–18]. Water loss occurs due to changes in water vapor pressure between the fruit and its surroundings, leading to alterations in textural properties and osmotic pressure [19,20].

Factors such as temperature, humidity, and air circulation within the storage environment play crucial roles in determining the rate of water loss. Low humidity levels and high temperatures can expedite water evaporation from the fruit's surface. The water vapor deficit and

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respiratory activity are linked to the permeability of water from the fruit to the surface [21–24]. Additionally, factors like the fruit's maturity stage, morphological characteristics, surface damage, and atmospheric pressure can significantly influence water loss in fresh produce [22,25,26].

Managing water loss is a critical challenge in extending the shelf life of fresh produce during postharvest processes. Controlling the rate of water loss is essential to maintain the desired appearance and texture of the produce [27]. Even under the same storage conditions, the rate of water loss in fruit can vary due to varietal differences [6]. Sherman et al. [28] conducted an experiment with different squash cultivars stored under identical conditions and found variations in weight loss among the cultivars after storage. The susceptibility of fruits to water loss is influenced by their textural properties, with softer fruits losing water at a higher rate than firmer ones [5,29]. According to Paull and Chen [30], papayas lose water through stomata and cuticle, and the rate of water loss is linked to the size and thickness of the cuticle. Mangoes are dense and have low porosity (0.04–0.05) compared to fruits like pineapple (0.16–0.25), apple (0.18–0.22), and strawberry (0.47). This density and low porosity result in greater resistance to mass transfer due to their tissue structure [31–35].

Firmness and texture are crucial in shaping consumers' perceptions of fruit quality, influencing overall flavour, taste, organoleptic qualities, marketability, and shelf life [36–38]. Water loss directly impacts firmness and texture by affecting cell turgor, cell size, solute transport, and the accumulation of osmotically active substances at the cellular level ([39]; Abrahao and Correa, 2023). Turgor pressure, exerted by cell walls, significantly contributes to fruit firmness. Water loss diminishes turgor pressure, causing cells to contract and the fruit to lose firmness. Turgor loss has been documented to reduce the firmness of various fruits including nectarines, potatoes, and apples [40–42].

Forney et al. [43] observed a decrease in firmness in high bush blueberries as water loss increased from 4 to 14 % over 3–9 weeks of storage. Paniagua et al. [12] confirmed a noticeable reduction in blueberry firmness due to increased water loss, suggesting that maintaining water loss below 8 % in blueberries could potentially retain firmness for up to three weeks of storage. The structural integrity of fruits relies on the cell wall, which provides support. As water is lost, the cell walls lose hydration and become stiffer, resulting in reduced elasticity and firmness. This ultimately affects the fruit's texture by making it softer and less crisp. In more severe cases of water loss, cells can collapse, leading to a loss of structural integrity and overall firmness. This often manifests as shrivelling or wilting in fruits, rendering them dry and brittle by transforming their structure from juicy and crisp to tough and leathery. Such changes impact the overall sensory experience and increase the fruit's vulnerability to pathogens.

Currently, there is a lack of comprehensive information on water loss and its mechanisms in postharvest fruit technology. Recent critical reviews in this field, particularly concerning fruits, are limited. Most research and literature focus primarily on strategies to mitigate water loss, extend shelf life, and preserve fruit quality during postharvest handling and storage. This paper aims to elucidate the mechanisms of water loss, its impact on fruit quality, the influencing factors, and the latest advancements in control strategies within postharvest fruit technology. Understanding the mechanisms and contributors to water loss in fruits is crucial for developing effective postharvest practices that benefit the entire fruit supply chain. This review provides a foundation for informed decision-making and the implementation of practical strategies tailored to various fruit types, varieties, and storage conditions, ultimately enhancing fruit quality and market value.

1.1. Mechanism of water loss in fruit

The mechanism of water loss in fruits is primarily driven by the process of transpiration. Transpiration processes contribute to the loss of water from tissues leading to dehydration and reduced fruit quality. Water loss occurs primarily through the fruit's surface and is driven by a combination of factors including temperature, humidity, air movement, and the fruit internal physiological processes. The primary mechanisms contributing to water loss in fruits encompass various structures such as the cuticle, epidermis, stomata, lenticels, mesocarp, and vascular system. These components regulate transpiration and gas exchange, thereby influencing the rate of water loss, which can vary based on varietal differences. Table 1 displays the percentages of water loss and how it may impact the overall fruit quality.

Transpiration is the process by which water is lost from the fruit's surface in the form of water vapor. It occurs through tiny pores called stomata present on the fruit's outer skin also known as epidermis. Transpiration is responsible for the majority of water loss in tomatoes accounting for approximately 92 %–97 % [29,45,46]. This process involves water moving from the fruit's interior through its tissues to the epidermis where it subsequently evaporates through the stomata into the surrounding atmosphere. As transpiration proceeds, the fruit's tissue starts to dry out and the stomata close reducing the transpiration rate along this route [47–49]. In this context, it's worth noting that stomata do not play a predominant role in the overall rate of water loss, transpiration primarily occurs directly from the epidermal cells through the apoplast [50,51]. In addition to transpiration through stomata, the stem scar and carlyx have been identified as contributors to fruit transpiration [52]. In the case of pepper fruit, due to the absence of stomata, transpiration primarily occurs through the skin's cuticle with support from the carlyx [52]. The cuticle, comprising waxes and cutin plays a pivotal role in transpiration and gas exchange regulation ([53,54]; Schreiber and Schonherr, 2009; Reiderer and Schreiber, 2001 [55]). Fig. 1 illustrates how mango fruit undergo changes in the overall quality due to water loss caused by transpiration and respiration processes, thus results in dehydration. Additionally, the movement of O_2 and CO_2 within the fruit promotes the production of ethylene and encourages water transpiration into the surrounding environment.

In tomatoes, the majority of the transpiration (67 %) happens through the stem scar [56], whereas in eggplants the carlyx accounts for 60 % of the transpiration process [57]. Kritzinger and Lotze [58] reported that the cuticles played a significant role in water loss in Japanese plums, with lenticels not being the determining factor for fruit permeability. Lenticels are tiny opening on mango fruit skin responsible for transpiration and gas exchange [59], and developed by stomata during the fruit enlargement and growth [60,61]. In mangoes, transpiration and gas exchange primarily occur through lenticels and the rate of transpiration depends on their size and number [62,63]. As banana ripen, the conversion of starch into sugar increases the osmotic potential difference between the pulp and the skin leading to water diffusion from the skin to the pulp resulting in water loss and shrinkage [64,65]. This shrinkage, in turn, causes excessive water loss from the skin to the surrounding fruit [65].

Table 1
Effect of water loss on the quality of fruits [44].

Water loss (%)	Potential effects
0.5 %	Increased activity of some cell wall enzyme.
1 %	Increased CO_2 and ethylene production. Faster ripening, yellowing and abscission. Reduce wound healing (periderm formation).
2 %	Reduced turgor. Reduced susceptibility to chilling injury. Accelerated loss of volatiles.
3 %	Loss of membrane integrity.
4 %	Faster loss of vitamins A and C. loss of flavour. Discoloration of mechanical injury.
5 %	Loss of colour intensity and gloss. Increase severity of pitting associated with chilling injury. Wilting and shrivelling.
6 %	Loss of textural quality: softening, limpness, flaccidity, and loss of crispness and juiciness.

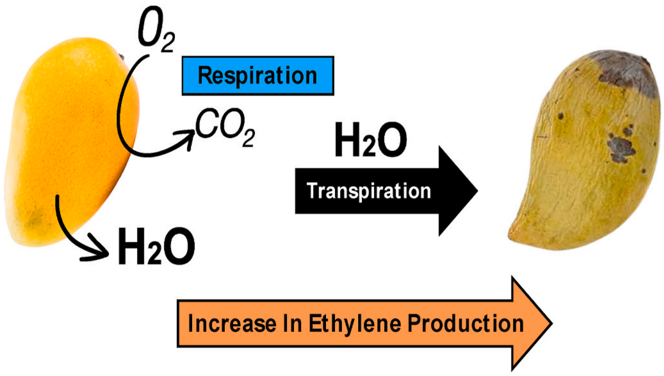

Fig. 1. Mechanism of water loss in mango fruit through transpiration and respiration processes.

1.2. Factors contributing to water loss in fruit during postharvest

Water loss in fruit during the postharvest period is influenced by various factors related to handling, storage, and environmental conditions. These factors contribute to the overall rate of water loss and can significantly impact the fruit quality and shelf life. Some key pre-harvest and postharvest factors contributing to water loss in fruit include: agricultural practices, storage conditions, storage duration, postharvest treatments, mechanical damage, type of fruit, fruit size, and fruit maturity.

1.2.1. Agricultural practices

Pre-harvest management practices encompass a range of agricultural activities aimed at optimizing crop yield and quality. However, these practices can inadvertently contribute to water loss in fruits, leading to adverse outcomes. The frequency, timing, and method of irrigation can significantly influence the water content in fruits. Over-irrigation or irregular watering schedules can lead to fruits with higher initial water content, which are prone to rapid water loss post-harvest. Conversely, under-irrigation can cause stress, leading to lower water retention in fruits. Efficient water management is crucial for maintaining crop quality and maximizing yield [66]. Studies have shown that deficit irrigation reduces water accumulation in fruits and fresh fruit yield but increases total soluble solids in tomatoes [67]. High levels of moisture stress adversely affect both yield and quality by decreasing cell enlargement.

The type and number of fertilizers used can impact the cellular structure of fruits. Excessive use of nitrogen fertilizers can lead to larger fruits with thinner skins, which are more susceptible to water loss. Nutrient balance is crucial for maintaining optimal fruit texture and size. Fruits from nitrogen-deficient trees are usually smaller with a firmer texture, while excess nitrogen causes water loss, rapid loss of firmness, and decreased storability. Potassium deficiency also leads to textural changes, resulting in water loss, small and poorly coloured fruits that may not ripen, leaving them hard and inedible. A lack of boron can result in fruits with a mealy texture [68]. Poor fertilizer management increases physiological disorders due to mineral deficiencies or toxicities, both of which negatively affect fruit quality and lead to water loss. Therefore, balanced fertilization practices are crucial to ensure the structural integrity of the fruit skin, reducing transpiration rates. However, the use of pesticides and growth regulators can affect the physiological processes in fruits. Some chemicals can alter the cuticle thickness or the stomatal behaviour, influencing the rate of water loss. Understanding the long-term effects of these applications is important for managing water retention in fruits. The timing of harvest plays a critical role in determining the water content in fruits. Fruits harvested at peak ripeness may have higher water content and are more prone to dehydration. Harvesting at the optimal time, considering the intended storage and transportation conditions, can help mitigate water loss.

The harvest seasons for various fresh produce worldwide coincide with diverse weather conditions such as sunshine intensity, wind speed, rainfall, and temperature, as well as climatic seasons like dry, hot, wet, and cold periods. The significant heat accompanying fruit harvested during hot times of the day can trigger high respiration and transpiration rates, leading to rapid water loss and quality deterioration during prolonged storage [69,70]. To mitigate this, it is recommended to apply pre-cooling treatment immediately after harvest before prolonged storage [69,71]. Additionally, during hot days and seasons, harvesting is commonly done very early in the morning or late in the evening when the environment is naturally cooler than midday. Conversely, fruit harvested immediately after heavy rainfall is more susceptible to high rates of water loss during storage due to increased turgor pressure within the product tissues. In such scenarios, subjecting the fruit to conditions that allow the loss of excess moisture is crucial. For example, a conditioned moisture loss of about 3 % prevents fruit decay and minimizes further moisture loss in citrus fruit [29,72]. Therefore, environmental conditions should be carefully considered during fruit harvesting to minimize the energy requirements of pre-treatment or preconditioning steps.

1.2.2. Fruit type

Different fruit types contribute to water loss in various ways due to their unique physical and physiological characteristics. The susceptibility to water loss can vary based on factors such as skin thickness, cuticle composition, internal structure, and metabolic activity. Stone fruits including peaches, plums, and nectarines have relatively thicker skins. As they ripen, changes in their internal structure and metabolic activity can lead to increased water loss through the skin. Water loss was assessed for plum, apricot, peach, and nectarines [73–75], under comparable storage conditions revealing a lower water loss percentage (ranging from 0.17 % to 0.31 % d^{-1}) in plums compared to nectarines and peaches which is attributed to their varietal characteristics [76]. In the case of pears and apples, both were examined under uniform storage conditions at 20 °C and 95 % relative humidity, and it was observed that pears experienced higher water loss than apples over the course of storage [77,78]. Despite the thicker skins and protective cuticles present in pome fruit like apples and pears, water loss can still occur through the stem or carlyx regions as well as through any surface damage or punctures.

Moisture rich fruit like tomatoes and cucumbers contain a substantial amount of water and are susceptible to water loss due to their cellular makeup. Any wounds, cuts, or skin damage can accelerate the water loss in such fleshy fruit. in the case of tomatoes, peppers, and eggplants, the carlyx (stem scar) is responsible for more water loss compared to their waxy cuticles [6,79], with approximately 60 %–70 % of water loss occurring through the carlyx, notably higher than the 2 % seen in apples [57,80,79]. Tropical fruit like papayas and mangoes have relatively thicker skins making them more tolerant of mild dehydration. However, their vulnerability to water loss increases as they ripen and their internal cells soften. Watermelons and cantaloupes with their high-water content are also prone to water loss. Their porous rind and spacious internal cavities facilitate moisture evaporation.

1.2.3. Fruit size

Fruit size can significantly contribute to water loss in fruits due to the larger surface area exposed to the surrounding environment. As the surface area increases with fruit size, there is more space available for water retention in the fruit's surface. This can lead to lower rates of water loss especially in larger fruits [81]. The size of a fruit is directly linked to its surface area with larger fruit having a greater surface area in relation to their volume compared to smaller ones. Diaz-Perez et al. [52] found that as bell peppers increased in size and ripeness, their water loss decreased. Similarly, Maguire et al. [9] observed that smaller apples experienced a higher percentage of water loss compared to their larger counterparts. Additionally, in pear fruit, the neck area loses water at a faster rate than the larger area at the bottom of the fruit [82].

Transpiration in fruit diminishes as their size increases and this phenomenon has been observed in eggplants, bell peppers, and tomatoes [83,79]. The size of the fruit can hold significant commercial importance due to its direct influence on transpiration and its ability to reduce water loss in the fruit. Diaz-Perez [79] reported that smaller eggplants exhibited a higher transpiration rate at 1.12 % per day/kPa, in contrast to larger eggplants which had a rate of 0.62 % per day/kPa. As the size of the fruit increases, the surface area-to-volume ratio decreases. Smaller eggplants were found to have a higher surface area-to-weight ratio resulting in an increased transpiration rate compared to larger eggplants [79]. In the case of tomatoes, the extent of water loss was found to be linked to the surface area-to-volume ratio of the fruit [84].

1.2.4. *Fruit maturity*

Fruit maturity significantly influences water loss, with physiological and structural changes occurring at different maturity stages impacting susceptibility to water loss. Factors such as alterations in cell structure, cuticle development, respiration rates, and metabolic activity contribute to the relationship between fruit maturity and water loss. As fruit mature, loosely connected cells and increased intercellular spaces provide pathways for water vapor to escape, accelerating water loss. Chomchalow et al. [85] observed less water loss in matured tomatoes compared to least matured tomatoes at 12.5 °C for 1 day storage time. In some cases, higher rate of water loss is observed as the maturity level increases in fruit. However, variations exist with observations of increased water loss in mature strawberries compared to less matured ones [86]. Similarly, persimmons and sweet bell peppers exhibit increased water loss with advancing maturity stages during storage [87]. Also, water loss of sweet bell peppers increases with the increase in the maturity level during the cold storage for 28 days [88]. Over-matured fruit are particularly susceptible to water loss [29,89].

1.2.5. *Mechanical injury*

Mechanical injuries also refer to as physical injuries or bruises can contribute to water loss in fruit by damaging the protective outer layer of a fruit's skin. Mechanical injuries such as cuts, scratches, or bruises can disrupt or damage the cuticle. This damage compromises the barrier function of the cuticle allowing water to escape more readily. According to FAO [90], approximately 31 % of fruit loss is attributed to factors like weight loss, bruises, and decay, significantly impacting their commercial value. Bruises, a common mechanical injury during postharvest processes occur due to excessive loads or external forces during handling and transportation [91,92]. Bruises can damage the cell structure and integrity of the fruit, leading to collapsed cells and tissue, creating pathways for water to escape [93–95]. The compromised quality of bruised fruit affects appearance, taste, and nutritional content with increased susceptibility to decay pathogen attacks. Bruising also influences physiochemical processes, increasing transpiration and ultimately reduce fruit quality and shelf life [96–98].

Li et al. [99] found that the loading position had a gradual and significant impact on water loss, ranging from 12 % to 16 % during the storage of tomato fruit. Bruising has been associated with increased carbon dioxide evolution and ethylene production, altering the physicochemical properties of locule and pericarp tissues, thereby diminishing fruit quality [100]. Apples with bruises exhibit heightened susceptibility to fungal and bacterial contamination, resulting in a shortened storage shelf life [101,102]. Godoy-Beltrame et al. [103] reported that mechanical in papaya fruit led to increased respiratory activity, ethylene production, and heightened susceptibility to water loss, affecting the overall fruit physiology. Mechanical injuries have been linked to increased transpiration, respiration, and reduced shelf life in various fruit, as noted in studies on different fruit such as tomatoes, apples, papayas, and bananas [104,105]. Bananas experienced an 11.2 %–11.8 % increase in water loss due to mechanical damage after 9 days of storage [106]. Zhu et al. [107] observed increased water loss in harvested apple fruit subjected to compressive forces of 80, 160, 320, and 640 N. Bruising significantly impacted the overall quality of 'Carabao' mango, contributing to increased water loss throughout the process [108].

1.2.6. *Storage conditions*

Storage conditions play a crucial role in contributing to water loss in fruit, leading to undesired alterations in texture, appearance, flavour, and overall quality. Conditions with low relative humidity can facilitate moisture release from fruit. Fruit being hygroscopic, release moisture to the environment when exposed to drier air. Maintaining optimal humidity levels (typically between 85 and 90 % relative humidity for most fruit) and a temperature range of 4 °C–7 °C proves to be effective in minimizing water loss in figs, mizuna, and eggplants [109], mushrooms [110], and pomegranate arils [22]. Transpiration is commonly influenced by factors such as relative humidity, surface area, temperature, respiration rate, and air movement [110–112].

Elevated temperatures can intensify the evaporation of water from the fruit surface, expediting the drying process and leading to accelerated water loss. Lowering the storage temperature in conjunction with high relative humidity proves to be effective in mitigating the overall rate of water loss [22,110,113]. For instance, in pomegranate arils, water loss decreased with increased relative humidity (96 %) and decreased temperature (5 °C), while transpiration rate rose with reduced relative humidity (76 %) and increased temperature (15 °C) [22]. Similar effects were observed in mushrooms [110], strawberries [24], grape tomatoes [78]. Recommended storage conditions for preserving grape quality include low temperature at 0 °C [114] and high relative humidity at 95 % [115,116]. Water loss persists even at 100 % relative humidity, with condensation forming as perspiration on the fruit surface [24,117]. Increased air flow rate enhances the transpiration rate, causing excessive water loss in fruit [29]. The impact of air flow on water loss is more pronounced at low vapor pressure deficit in both the fruit and the environment [29,118]. Storage duration has also been identified as a contributor to water loss in various fruit with longer storage periods allowing more time for moisture loss [22,119]. Prolonged storage under unfavourable conditions can exacerbate water loss.

1.2.7. *Postharvest treatments*

Cleaning fruit is vital to eliminate dirt, contaminants, and residues, yet these procedures may induce water absorption by the fruit. Following washing, fruit can experience surface drying, undergoing moisture loss through evaporation. Drying and curing aimed at controlled dehydration to reduce moisture content and influence water loss by affecting the fruit's overall texture and quality. Hot water treatment is used to eliminate pest and pathogens from fruit [120–122]. Exposure to hot water can lead to an increase in water loss due to increased evaporation from the fruit's surface. The quality of fruit during hot water treatment is notably affected by treatment temperature and duration [123,124]. For instance, Satsuma mandarin fruit exhibited increased water loss with hot water treatment [125,126], while short treatments reduced water loss in cucumbers with higher temperatures [121,127]. Precooling employed for swift temperature reduction postharvest may lead to excess water condensation on the fruit's surface during inadequate control, resulting in water loss during subsequent storage.

Fruit packaging and packing play crucial roles in maintaining the quality and extending the shelf life of postharvest fruits. However, they can also contribute to water loss if not done properly. Packaging materials that are too permeable to water vapor can lead to increased water loss from the fruit [29,119]. This is because water vapor can easily escape from the fruit into the surrounding air. Packaging that does not provide an adequate barrier to water vapor transmission can result in dehydration [128]. For instance, packaging materials that do not have sufficient thickness or are not coated to prevent moisture loss can exacerbate water loss. Packaging that lacks adequate ventilation can create an environment where moisture accumulates. This can lead to condensation inside the package, which can then be reabsorbed by the fruit, leading to quality degradation. Packaging that does not provide sufficient insulation can expose fruits to temperature extremes, further accelerating water loss and potentially causing chilling injuries that compromise fruit quality.

1.3. Control strategies for water loss in fruit postharvest

1.3.1. Selection of resistant varieties

Genetic diversity within fruit species provides a foundation for selecting varieties that are naturally more resistant to water loss. Plant breeders can identify and propagate these varieties through traditional breeding methods or modern biotechnological techniques [129]. The key is to select varieties that exhibit traits such as thicker skin, smaller stomatal aperture, and reduced cuticular transpiration. Resistant fruit varieties typically possess several beneficial traits. A thicker cuticle acts as a barrier to water loss by reducing cuticular transpiration. Smaller stomata reduce the rate of transpiration, helping to conserve water within the fruit [29]. Varieties that have evolved in arid regions often have built-in mechanisms to conserve water. Some varieties have better water retention capabilities, reducing dehydration during storage and transport. Several resistant varieties have been identified across different fruit species. For example, certain apple varieties like 'Honeycrisp' have been bred for their ability to retain water better than others [130]. Similarly, grape varieties used for raisins are selected for their thicker skins and lower transpiration rates [131,132].

1.3.2. Application of anti-transpirant substances

Anti-transpirants are substances applied to the surface of fruits to reduce water loss. They work by forming a protective film over the fruit surface or by inducing physiological changes that reduce transpiration. Anti-transpirants can be classified into two main types: film-forming and metabolic inhibitors. Film-forming anti-transpirants create a physical barrier that reduces water vapor loss [133]. Common materials used include waxes and oils, synthetic Polymers such as polyvinyl alcohol (PVA) and polyethylene glycol (PEG), natural Polymers such as chitosan and other biopolymers. Metabolic inhibitors reduce water loss by affecting the plant's physiological processes. They work by closing stomata or reducing the metabolic activity that leads to transpiration. Common metabolic inhibitors include abscisic acid (ABA) and fungal extracts. Certain fungal extracts can reduce transpiration rates by influencing plant metabolism. The application of anti-transpirants involves spraying the substances onto the fruit surface. Proper application ensures uniform coverage and effective reduction in water loss. Factors such as concentration, timing, and environmental conditions are critical for optimal results. Anti-transpirants offer several benefits in mitigating water loss, maintain the fruit quality, and extend the shelf life [134]. Numerous studies have demonstrated the efficacy of anti-transpirants in reducing water loss. For instance, research on tomatoes and apples has shown significant reductions in weight loss and improved shelf life when treated with wax-based anti-transpirants [135]. Similarly, grapes treated with ABA have exhibited lower rates of transpiration and better retention of water [136,137].

1.3.3. Storage conditions

Transpiration rates depends on storage relative humidity. Fruit maintains optimal quality and retain their sealable weight under high relative humidity, minimizing vulnerability to softening, water loss, and wilting. External factors like atmospheric pressure, air velocity, temperature, and humidity influence fruit transpiration rates. Higher temperatures, increased air velocity, and lower relative humidity elevate transpiration rates. Room temperature affects respiration and metabolic processes, with high respiration making fruit more susceptible to deterioration. Conversely, lower temperatures reduce ripening and respiration rates, extending the storage shelf life and minimizing susceptibility to pathogenic fungi. Fruit requiring warm temperatures (40 °F to 55 °F) can be harmed at freezing temperatures (32 °F), emphasizing the risks of both extremely high and low temperatures [138]. Different fruit varieties have distinct characteristics including varying compositions, textures, and sensitivities to environmental factors. These differences lead to varied optimal storage conditions to maintain freshness and quality. Factors such as sugar content, water content, thickness of the skin, and susceptibility to chilling or freezing injury contribute to the specific storage requirements of each fruit variety. Tailoring storage conditions to the unique needs of different fruit helps preserve their taste, texture, and nutritional value while minimizing the risk of spoilage or damage. Table 2 displays the recommended storage conditions, estimated storage life, and freezing points for various fruit varieties.

1.3.4. Precooling

Precooling methods are widely employed in postharvest practices to mitigate water loss and preserve the quality of fruit. The precooling process for fruit is a post-harvest treatment designed to quickly reduce the temperature of freshly harvested fruit to its optimal storage or transportation temperature. The primary goal of precooling is to slow down the metabolic processes and reduce the respiration rate of the produce, thereby extending its shelf life and maintaining quality [138]. This process helps to minimize the loss of water, reduce the risk of decay, and preserve the freshness, texture, flavour, and nutritional value of the produce [14]. The application of precooling treatments reduces the

Table 2
Fruit and their recommended storage conditions.

Fruits	Temperature (^{0}C)	Relative Humidity (%)	Approximate Storage life	Freezing Point (^{0}C)
Apples	-1–4.5	90–95	4–32 weeks	−2
	2–4.5	95		
Apricots	−0.5–0	85–95	1–3 weeks	−1.056
Blackberry	−0.5–0	85–100	2–3 days	−0.83
Currants	−0.5–0	90–95	1–2 weeks	−1
Strawberries	−0.5–0	90–95	3–7 days	−0.7
Cherries, sour	0	90–95	3–7 days	−1.6
Cherries, sweet	-1–0	85–95	2–3 weeks	−1.7
Grapes	-1–0	85–95	12–24 weeks	−1.27
Nectarines	−0.5–0	85–90	1–6 weeks	−0.88
Peaches	−0.5–0	85–95	2–6 weeks	−0.94
pears	-2–0	90–95	8–28 weeks	−1.55
Plums and prunes	−0.5–0	85–95	1–7 weeks	−0.83
Quinces	−0.5–0	85–90	8–12 weeks	−2
Mango	10–13	85–90	2–3 weeks	−1
Banana	13.5–15	85–95	2–5 days	−0.83
	12.5–21		4–21 days	
Durian	10	90	1 week	
Fig	-1–0	85–95	1–3 weeks	
Guava	7–10	90	2–3 weeks	−4
Kiwi fruit	−0.5–0	90–95	8–16 weeks	−2
Lemon	0–5	85–90	2–3 weeks	26
	14.5–15.5		4–24 weeks	
Lime	7–10	85–90	4–10 weeks	26
Mandarin	5–7	85–90	2–8 weeks	26
Orange	0–9	85–90	3–16 weeks	26
Pawpaw	7–13	85–90	1–3 weeks	0
Pineapple	5–7	85–90	2–4 weeks	−1.4
	10–20			
Pomegranate	0–5	85–90	8–16 weeks	-3–5
Tangerine	0–3.5	85–90	2–4 weeks	
Avocado	0–2	85–95	10 days	
	4.5–13		2–4 weeks	

Source: Department of Primary Industries and Regional Development's Agriculture and Food division, Australia. https://www.agric.wa.gov.au/fruit/storage-fresh-fruit-and-vegetables?page=0%2C0 temperature needed in cold storage, preventing temperature fluctuations [139]. Fruit stored in cold environment without prior precooling may experience reduced storage life due to potential temperature variations [140]. Various precooling techniques such as vacuum cooling, liquid ice cooling, hydrocooling, and forced air cooling are employed to achieve these beneficial effects [138].

Room cooling involves placing fruit in a refrigerated room for temporary storage, although at a slower rate compared to other cooling methods [140,141]. Enhanced efficiency in room cooling can be achieved by introducing high air flow rates, elevating the local surface heat transfer coefficient. Forced air cooling, which directs cold air through containers of fruit is applicable to bulk and palletized produce [142,143]. Essential considerations in forced air cooling include air velocity and temperature [144,145]. Hydrocooling, an effective yet traditional technique, employs the high heat transfer coefficient of water. This method involves spraying cold water on fruit using shower equipment or immersing the fruit directly into a cold-water mixture [146,147]. However, hydrocooling may not be suitable for all fruit, particularly strawberries, as full immersion in cold water can potentially damage the fruit [148].

Vacuum cooling achieves rapid temperature reduction by evaporating moisture from the fruit surface and within the fruit. To minimize water loss, water can be sprayed on the fruit before placing them in the vacuum chamber [149]. However, different fruit varieties may require distinct precooling systems due to variation in size, shape, skin thickness, and overall composition. Fruit with varying characteristics may respond differently to cooling methods. For instance, berries with delicate skin might be more susceptible to moisture loss during precooling, so a system that minimizes dehydration would be preferable. On the other hand, fruit with thicker skins might need a different approach to ensure effective cooling. Additionally, some fruit like banana and apple are more sensitive to chilling injury, a condition that occurs when fruit are exposed to temperatures that are too low for their specific chilling threshold. Therefore, the precooling system needs to consider the optimal temperature range for each fruit variety to prevent damage. Table 3 provides information about the recommended precooling methods, storage conditions, and the corresponding suitable shelf life for different varieties of fruit.

1.3.5. *Humidification*

Maintaining relative humidity levels within the range of 85 %–95 % is recommended to minimize water loss and preserve fruit quality [150–152]. The use of techniques like atomized or stem water droplets, under carefully controlled conditions, has proven effective in reducing water condensation on fruit [29]. Excessive condensation on fruit can increase susceptibility to pathogen attack, leading to decay and loss [8,153]. However, subjecting packaging cartons to high humidity conditions may reduce their compression strength, potentially causing damage to stacked items [102,154–156]. Delele et al. [157] reported that a high humidity environment can affect the evaporator of the cooling unit by freezing water vapor.

Mist spray humidifiers, which are extensively employed in the industry to regulate water loss in fruit, encompass four main types: rotary atomizers, air-assisted, ultrasonic, and high pressure [29]. Air-assisted atomizers may not be suitable under ultra-low oxygen conditions, as they require external air addition, potentially altering the gas composition in such environments. Rotary atomizers, on the other hand, are reported for their complexity [29,158]. Ngcobo et al. [159] utilized an air-assisted humidifier with table grapes, producing an average water droplets size of 10 μm for humidifying storage rooms at 95 % relative humidity and −0.33 °C. Mist spraying, coupled with an ultrasonic humidification system maintaining around 95 %–100 % relative humidity in a cabinet, demonstrated effectiveness in reducing water loss and deterioration in various fruit during storage [153,160]. Mohammed and Alqahtani [161] designed sensor-based artificial system as a promising approach for ripening date palm Biser fruit and found that the system ripened date fruit with high quality attributes in terms of weight, colour, density, firmness, sugars, pH, and total soluble solids.

1.3.6. *Edible coating*

Edible coatings are valuable tool for controlling water loss in fruit during postharvest storage and transportation. These coatings create a protective barrier on the fruit's surface by reducing the rate of water evaporation and helping to maintain the fruit's quality and freshness. As presented in Fig. 2, edible coatings decelerate the water vapor diffusion from the fruit, thereby reducing transpiration and limiting water loss. These coatings can regulate gas exchange including the exchange of water vapor, oxygen, and carbon dioxide. By controlling the movement of gases, coatings can help maintain the optimal humidity level around the fruit and prevent excessive water loss.

Edible coating materials can be categorised into polysaccharide-based, lipid-based, protein-based, and composite coatings [162,163].

Table 3

Recommended precooling methods and storage conditions for fruits.

Fruits	Temperature (^{0}F)	Relative humidity (%)	Precooling method	Storage life days	Ethylene sensitive
Apples	30–40	90–95	R, H, F	90–240	Y
Apricots	32	90–95	R, H	7–14	Y
Avocados	40–55	85–90		14–28	Y
Bananas	56–58	90–95		7–28	Y
Blackberries	31–32	90–95	R, F	2–3	
Blueberries	31–32	90–95	R, F	10–18	
Cherries, sweet	30–31	90–95	H, F	14–21	
Cucumbers	50–55	95	F, H	10–14	Y
Grapefruit	50–60	85–90		28–42	
Grapes	32	85	F	56–180	
Kiwifruit	32	95–100		28–84	Y
Lemons	50–55	85–90		30–180	
Limes	48–50	85–90		21–35	
Nectarines	31–32	95	F, H	14–18	Y
Oranges	32–48	85–90		21–56	
Peaches	31–32	90–95	F, H	14–28	Y
Pears	32	90–95	F, R, H	60–90	Y
Pineapple	45–55	85–90		14–36	
Strawberries	32	90–95	R, F	5–10	
Tomatoes	62–68	90–95	R, F	7–28	Y
Watermelon	50–60	90	N	14–21	

F = forced-air cooling, H = hydrocooling, I = package icing, R = room cooling, V = vacuum cooling, N = no precooling needed. Y = yes. Source: USDA Agricultural Marketing Service, Kansas State University Cooperative Extension Service.

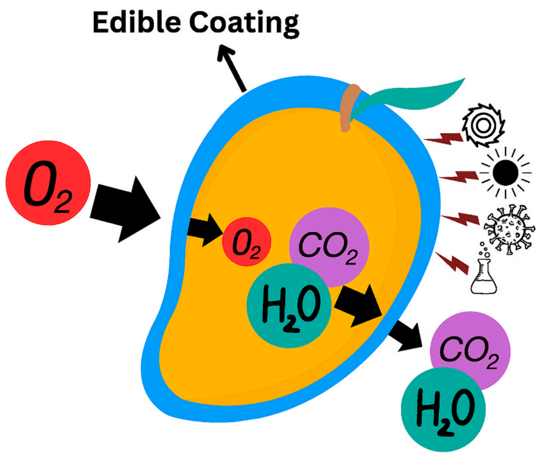

Fig. 2. Functions of edible coatings on fruit.

Lipid-based coatings exhibit effective water barrier properties, reducing water transfer, whereas polysaccharide-based coatings may have limited water vapor barrier and low gas permeability. Protein-based coatings offer favourable mechanical properties [164]. Plasticizers, solvents, and resins are utilized to achieve specific characteristics. Chitosan coatings, known for excellent oxygen barriers, have been shown to decrease fruit ripening and transpiration [165]. Application of chitosan coatings on Cavendish bananas reduced decay, ripening, and water loss [166]. Cellulose-based coatings are commonly used to hinder moisture and gas transpiration in fruit [167]. Cassava starch enhanced resistance to water loss in strawberries by improving sensory acceptance [168]. Incorporating lemongrass essential oil into cassava edible coating reduced weight loss and microbial growth in papaya fruit [169]. Aloe vera gel coatings decreased water loss by reducing respiration rates in table grapes and mitigated browning during storage [170].

Protein-based coatings are sensitive to environmental conditions like humidity and temperature during storage [171]. Lipid-based coatings, known for their effective water barrier properties, enhance the visual appeal of fruit due to their natural shine [172,173]. Coatings composed of sucrose esters of fatty acids significantly reduce weight loss and maintain the firmness of cherries during storage [174]. Composite coatings, such as shellac-tannic acid coatings have been shown to extend the shelf life of mangoes by preserving firmness and minimizing water loss at room temperature. The antifungal activity of the coating is enhanced by the presence of tannic acid [175]. Incorporating nano and micro-sized carnauba wax ginger essential oil and hydroxypropyl methylcellulose reduces firmness loss, colour changes, water loss, and respiration rates in papaya fruit [176]. Table 4 illustrates the efficacy of various combinations of compounds used as edible coatings under different storage conditions for preserving the quality and freshness of different fruit varieties.

1.3.7. New modified coating techniques

New and improved coating techniques are being developed to overcome challenges associated with edible coating materials, offering significant potential to reduce postharvest losses and enhance consumer satisfaction. These innovative coatings include nanostructured and composite coatings. Nanostructured coatings use nanoparticles or nanoemulsions to form a protective layer on fruits, which can improve mechanical strength, reduce microbial growth, and enhance sensory qualities. Research indicates that nanostructured coatings effectively inhibit spoilage microorganisms and extend the shelf life of fruits. The tightly packed structures formed by nanoparticles within the coating can block the entry of oxygen, moisture, and harmful microorganisms, significantly slowing spoilage processes [184]. Additionally, nano-encapsulation of essential oils or natural antimicrobials within the coating allows for targeted release, minimizing potential off-flavours and maximizing effectiveness [185,186].

Iturralde-Garcia et al. [187] utilized carvacrol-loaded zein nanoparticles as an edible coating for kiwi fruits and found that the coated fruits showed reduced microbial growth, improved firmness, and extended shelf life compared to untreated ones. Perdones et al. [188] discovered that incorporating chitosan with magnetic cellulose nanofiber enhanced the quality and mechanical properties of cut pineapple during storage under ambient conditions. Iniguez-Moreno et al. [189] demonstrated that chitosan nanoparticles combined with pomegranate peel extract improved microbial and physicochemical properties, maintaining the quality of fresh-cut pomegranate arils during refrigerated storage. Jose et al. [190] reported that chitosan integrated with nano-silicon dioxide exhibited better mechanical properties, an enhanced water vapor barrier, and significant antimicrobial activity against *E. coli* and *S. cerevisiae*, indicating their potential for fruit preservation. Pereira et al. [116] found that adding cinnamon essential oil to chitosan nanoparticles increased antimicrobial activity, reduced decay, and extended the shelf life of strawberries compared to the control group. Additionally, Vargas et al. [191] explored the use of nanoemulsion-based coatings incorporating antimicrobial agents to inhibit the growth of spoilage microorganisms and foodborne pathogens.

Table 4
Edible coatings on fruit quality preservation.

Main compounds	Additional compounds	Fruit	Storage conditions	Results	References
Nano and micro-sized carnauba wax emulsion	Ginger essential oil and hydroxypropyl methyl cellulose	papaya	6 days at 22 °C and 9 days at 13 °C followed by 5 days at 22 °C	Nanoemulsions preserved the quality of papaya and maintained the weight loss, firmness loss, and delayed ripening during storage.	Miranda et al. [176]
Chitosan	Essential oils	Strawberries and apples	Stored at cold storage (4 °C and 8 °C) for 7 days	The coating conserved the postharvest quality of apples and strawberries and increased their shelf life.	Popescu et al. [177]
Arabic gum		Mango fruit	20 days at 23 ± 2 °C and 45–60 % relative humidity	Maintained the quality of mangoes and delayed the ripening process.	Daisy et al. [178]
Oregano essential oil nanoemulsion		Tomatoes	14 days at 24 ± 1 °C	Improved the shelf life of tomatoes over 14 days and reduced the microbial growth and weight loss.	Pirozzi et al. [179]
Sucrose ester absorbic acid (AsA) and citric acid	Loquat leaf extract and alginate	Citrus fruits and Nanfeng Tangerines	60 days at 5 ± 1 °C	Reduced moisture loss, delayed nutrient degradation, and inhibited microorganisms in citrus fruits during the storage.	Zhang et al. [180]
Shellac (60 %)	Gelatin (40 %)	Banana	Low temperature (25 °C) for 30 days	The quality of banana was maintained with a slight reduction in weight and firmness.	Soradech et al. [181]
Chitosan	Magnetic cellulose nanofiber	Cut pineapples		The coating improved the quality of cut pineapple during the storage.	Ghosh et al. [182]
Chitosan	Alginate emulsion and Olive oil	Fig fruits	16 days storage time at 25 °C	Reduced the weight loss, respiration rate, and fungal decay of fig's fruits.	Win et al. [183]

Nanoemulsions, which consist of nanoscale oil droplets dispersed in water, have been employed to create edible coatings with enhanced barrier properties and functionality. These nano-sized droplets allow for superior penetration into the fruit's surface, facilitating the efficient delivery of bioactive compounds such as antimicrobials, antioxidants, and enzymes [192,193]. Resende et al. [194] found that cinnamaldehyde nanoemulsion combined with polylysine effectively inhibited microbial growth, reduced browning, and maintained the quality of fresh-cut apples during storage. A coating of chitosan, combined with alginate emulsion and olive oil, was shown to reduce the respiration rate, fungal decay, and weight loss of figs stored for 16 days at 25 °C. Gidado et al. [195] reported that a hydrophobic deep eutectic nanoemulsion coating decreased the incidence of anthracnose on mangoes due to its strong mode of action and binding affinity.

Gidado et al. [196] utilized a hydrophobic deep eutectic oil (Menthol-Thymol)-in-water nanoemulsion to conserve the quality of banana fruits. This treatment effectively preserved the fruit's physicochemical attributes, extending its shelf life by 14 days compared to the control group, which developed anthracnose disease and physical deterioration within 8 days of storage. Similarly, oregano essential oil nanoemulsion improved the shelf life of tomatoes by reducing microbial growth, with significant performance over 14 days at room temperature [179]. A nano and micro-sized carnauba wax emulsion combined with ginger essential oil and hydroxypropyl methylcellulose maintained papaya quality during storage by retarding firmness loss, weight loss, colour changes, and reducing respiration rates, resulting in delayed ripening [176]. Additionally, the application of a hydrophobic deep eutectic oil-in-water nanoemulsion coating significantly prolonged the shelf life of 'Harumanis' mangoes [197]. This treatment effectively slowed the ripening process, maintained fruit quality, and protected against anthracnose disease for up to 20 days of storage. In contrast, control fruits began to overripen and deteriorate after just 10 days.

Essential oils can be incorporated into composite coatings to provide additional functionalities. Composite coatings infused with essential oils have demonstrated enhanced antimicrobial efficacy and extended shelf life for various food products [198]. Research has explored the combination of chitosan, nanoclays, and plant extracts to create composite coatings with improved antimicrobial activity and mechanical strength [199]. For instance, a carboxymethyl cellulose coating with cardamom essential oil and glycerol significantly increased the shelf life of fresh tomatoes for 15 days at 25 ± 2 °C, maintaining quality throughout storage [200]. Peretto et al. [201] found that sucrose ester, ascorbic acid (AsA), and citric acid, combined with loquat leaf extract and alginate, effectively preserved citrus fruits and Nanfeng tangerines. This combination inhibited spoilage microorganisms, reduced moisture loss, delayed nutrient degradation, and enhanced antioxidant properties during cold storage for 60 days at 5 ± 1 °C. Additionally, a polyvinyl alcohol and silk fibroin coating exhibited high barrier properties, reducing weight loss, colour change, and moisture movement in coated apples after 14 days at 4 °C [202]. A shellac (60 %) and gelatin (40 %) combination slightly reduced weight loss and maintained the firmness and quality of bananas stored at 25 °C for 30 days [203].

1.3.8. Application of 1-methylcyclopropene (1-MCP)

Rapid ripening is a major factor contributing to water loss and swift deterioration of climacteric fruits post-harvest, commonly seen in apples, pears, mangoes, and papayas. Ethylene plays a crucial role in this process by promoting respiration and ripening [204]. The chemical compound 1-methylcyclopropene (1-MCP) binds to ethylene receptors in plants, acting as a competitive inhibitor [205]. This binding helps mitigate the effects of ethylene, thereby reducing quality loss in fresh produce [206]. The application of 1-MCP, both pre- and post-harvest, has shown significant success in various fruits, especially apples and pears [206,207]. Recent efforts have extended its use to fruits typically consumed when ripe, such as European pears, mangoes, papayas, bananas, tomatoes, and kiwifruit [208]. For apples, where ripening is unnecessary before consumption, it is vital to keep 1-MCP usage within the approved limit of 1 ppm or lower [209]. For other fruits, the 1-MCP dosage must be carefully balanced to extend storage life while allowing for ripening after storage, possibly with additional ripening treatments [208].

Research by Bai et al. [210] and Shu et al. [211] highlights the importance of skilfully manipulating 1-MCP application for optimal results. Effective strategies include delaying the application to stages of partial ripening [211] and reducing the dosage through a combined approach [210]. Dias et al. [208] have compiled the most effective methods for reversing 1-MCP effects, providing valuable insights into the postharvest management of climacteric fruits. Yuan et al. [212] explored 1-MCP treatment with or without melatonin on mangoes, noting improved visual quality and increased antioxidant enzyme activities. Prange and Wright [213] reviewed the additional effects of 1-MCP on apples and pears stored under controlled atmosphere (CA) conditions, finding that some cultivars can be stored at higher temperatures, potentially saving energy and enhancing quality. Shah et al. [95] reviewed advances in loquat storage technology, showing that 1-MCP treatment reduces chilling injury (CI) in loquat, inhibits reactive oxygen species (ROS) production, and maintains membrane integrity, thereby reducing internal browning and fruit decay.

2. Conclusion and future perspective

Postharvest water loss often referred to as weight loss or dehydration poses a significant challenge in fruit handling and storage impacting fruit quality, shelf life, and market value. Nearly half of fruit and vegetables are lost during postharvest processes, making it a crucial concern. Excessive water loss, even at modest levels, can lead to undesirable changes in texture and render the fruit unmarketable. The issues arise due to the fruit's susceptibility to water loss, affecting factors such as vulnerability to pathogen, flavour changes, and nutrient loss. Therefore, continued research is needed to develop and refine postharvest practices including handling, transportation, and storage to minimize water loss and maintain fruit quality. Further investigation into varietal differences in water loss susceptibility can contribute to the development of tailored solutions for different fruit types. Strategies to preserve fruit texture and firmness should be explored, considering the importance of these factors in consumer perceptions and overall fruit quality. In-depth studies on the cuticle and cell wall structures of various fruit can provide insights into their water loss resistance, guiding the development of targeted interventions. Continued effort to gather comprehensive information on water loss mechanisms, influencing factors, and advancement in control strategies will benefit the fruit supply chain. Bridging the gap between research findings and practical implementation is essential. Developing user-friendly guidelines for stakeholders in the fruit industry can facilitate the adoption of effective water loss mitigation strategies.

Ethical statement

N/A.

CRediT authorship contribution statement

M.J. Gidado: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Ahmad Anas Nagoor Gunny:** Supervision, Project administration, Conceptualization. **Subash C.B. Gopinath:** Supervision, Project administration, Conceptualization. **Asgar Ali:** Supervision, Project administration, Funding acquisition. **Chalermchai Wongs-Aree:** Supervision, Project administration, Funding acquisition. **Noor Hasyierah Mohd Salleh:** Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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