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Review Article

An Advancement in Postharvest Biology and Fresh-Keeping Technology of Kiwifruit (*Actinidia spp.*): A Review

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Abstract

Kiwifruit is a climacteric fruit that may decay rapidly and softens after harvest if not stored properly. How to expand the storage time of kiwifruit to maintain the quality, is a critical challenge for the kiwifruit industry development. Kiwifruit's post-harvest life is tied closely to post-harvest management, such as scientific harvesting, green preservation, ethylene management, and low-temperature storage, as well as texture and quality. This study focuses on the advancement of related research from four perspectives and explores their impacts on kiwifruit storage in order to give a theoretical foundation for breeding varieties with superior storage capacity, and the development of storage and preservation technologies. Hayward and Hort16A varieties of kiwifruit had been cultivated largely in past but now, yellow-fleshed Sun Gold, Gold 3 and Gold 9, Hongyang, Maohua Cuixiang, Xuxiang, etc. are becoming significantly famous in international commerce. For the best postharvest quality, kiwifruit must be stored at low temperatures. Fruit quality, harvesting maturity, ethylene production, storage life, green preservation, and pathology are the priorities in breeding projects. To take advantage of adequate germplasm resources, reproductive biology understandings are needed.

Keywords: Kiwifruit, Postharvest handling, Ethylene biosynthesis pathway, Pre-storage treatment, Postharvest Pathology.

1. INTRODUCTION

Actinidia chinensis and *Actinidia deliciosa* are both economically and agriculturally significant species of kiwifruit within the *Actinidia* genus. The *Actinidia* genus is known to encompass a total of 55 species and 76 taxa (Li *et al.*, 2009), however, this number is subject to change as new data becomes available. Kiwifruit is a nutrient-enriched food that contains high levels of antioxidants, folate, potassium, vitamins C and E. It also has natural laxative properties that can help relieve mild constipation (Lippi and Mattiuzzi, 2020). According to the latest data, global kiwifruit production exceeded 6.6 million tons in 2020 (Herforth *et al.*, 2020). However, China dominated global kiwifruit production in 2020, accounting for a staggering 68.2% of the harvested area and 50.6% of the world's total yield (Chen *et al.*, 2023). Kiwifruit may provide several health benefits i.e. decreasing arteriosclerosis, lowering the risk of certain cancers, irritable bowel syndrome and cardiovascular disease, and protecting cells from oxidative DNA damage in vitro (Pinto and Vilela, 2018). The commercialization of kiwifruit production has led to a surge in postharvest losses, which can significantly harm the fruit's overall quality. As a result, it's become increasingly important to mitigate these losses to sustain the kiwifruit industry.

Postharvest practices impact the quality of kiwifruit, including its sensory and nutritional properties. Key indicators of fruit quality include its morphological structures, as well as its physicochemical properties like titratable acidity (TA), soluble solids (SSC), ascorbic acid content (AAC) and firmness. (Xia *et al.*, 2020) states these are the factors to determine the fruit's level of

maturation, optimal harvesting time, and shelf life. Harvesting time is vital to achieve high commercial performance and improved quality of kiwifruit. Kiwifruit is typically harvested when matures (but unripen) at approximately 6.2° Brix (SSC) soluble solid content (Yi *et al.*, 2016). Wounding is a significant threat to kiwifruit during post-harvest handling. Research has shown that wounding can increase respiration in fruit and ethylene production rate (Watada *et al.*, 1996). The softening of kiwifruit is mainly attributed to ethylene production, although it has minimal impact on the fruit's appearance and skin (Crisosto and Garner, 2001). The susceptibility of kiwifruit to ethylene production causes its flesh to soften during cold storage, which directly impacts the fruit's shelf life (Boquete and Alvarez, 2004). Kiwifruit is stored in cold storage to extend its availability to consumers for a longer period of time, which leads to a significant rise in SSC and the presence of reducing sugars like fructose and glucose (Hu *et al.*, 2019). Studies have shown that there is a correlation between ethylene signaling and low temperatures, suggesting that the response to ethylene may be dependent on temperature (Wei *et al.*, 2022). Kiwifruit because of its tremendous ascorbic acid (ASA) content (which has a substantial role in postponing the fruit's senescence) is regarded as "King of Vitamin C" in China (Zhang *et al.*, 2021)

Kiwifruit is susceptible to postharvest pathogenic infections, particularly gray mold that is caused by *Botrytis cinerea*. This disease can cause extensive decay in the fruit with a huge economic loss in kiwifruit production. Various approaches have been studied to address this issue, including application of essential oils, biological control, and ozone treatment (Hua *et al.*, 2019). One of the major threats to the kiwifruit during post-harvest storage is soft rot (Manning *et al.*, 2016). To deal with these post-harvest challenges strategies need to be developed. This review demonstrates the essential methods for postharvest management, reiterates the current practices, and offers perspectives on forthcoming advancements in postharvest strategies for extended shelf life of kiwifruit.

2. Scientific harvesting and molecular changes after harvesting

Kiwifruit is typically harvested domestically from mid-October to April, and the stock for import and domestic consumption is available from May to November, making it possible to enjoy this fruit year-round. To ensure high-quality fruit and minimize postharvest losses, it's crucial to carefully select cultivars, harvest them at the right maturity stage, and distribute them properly from the production area. Apparently, there are no cultivar-specific maturity indices for kiwifruit harvest, but measuring the SSC (Meena *et al.*, 2018). At the time of harvest, various measurements are taken, such as weight, length and width, flesh color, SSC, dry matter (DM), firmness, respiration, and ethylene production. According to experiments conducted in controlled environments, it has been observed that elevated temperatures during the maturation of 'Hayward' fruit can lead to a significant reduction in DM (Wang *et al.*, 2021b). The time of harvesting has a significant impact on various quality parameters related to the maturity of kiwifruit, including SSC, DM, and firmness. While the SSC and DM levels tend to increase linearly with harvest time, the firmness decreases. A minimum SSC value of 6.2°Brix has been traditionally used for kiwifruit harvesting. Kiwifruit tends to soften over time, and fruits harvested later tend to be soften but maintained their firmness better while storage compared to early-harvested fruits. In conclusion, the study findings suggest that the timing of harvesting significantly affects the SSC, DM, and firmness of kiwifruit (Mahlaba *et al.*, 2022). Kiwifruit growers typically rely on sugar content to determine the best time to harvest their crops. However, using sugar content as the only maturity index may lead to mixed harvesting, resulting in reduced fruit quality and shorter storage life. To prevent this, growers can use a range of maturity indices i.e. chromaticity, starch tests, total degree days, or DAFB (days after full bloom), to accurately determine the harvesting time. Mixed harvesting can be costly for kiwifruit producers worldwide, with millions of dollars lost annually due to variations in storage period between and within fruit clutch (Feng *et al.*, 2002). Ethylene production gradually increases over time, as studies showed that during the first 2 months of ripening, ethylene production is relatively low and then suddenly increases to reach its peak during the climacteric phase. Late-harvested (180 DAFB) fruit exhibited the highest respiration rate (Han Ryul *et al.*, 2019). During the harvest and early storage days, there are noticeable differences in TSS and TA at different harvest times. Nevertheless, all the Hayward cultivars had statistically similar TSS and TA values, which exhibited an upward and downward trend throughout the storage life. Higher TA was observed at the time of harvest, particularly for the fruit harvested early (at 160 DAFB); however, it decreased as the harvesting time prolonged (Tilahun *et al.*, 2017). However, sensory evaluation of the kiwifruit suggests, harvesting at 160 DAFB possessed improved eating quality.

Postharvest physiology of kiwifruit aims to enhance fruit quality during storage using biochemical and physiological processes, with a focus on ethylene as a crucial factor due to its role in seed germination, development, growth, and responses to stress (Yahia, 2019). Ethephon (an ethylene stimulator) accelerates fruit senescence, while (1-MCP) 1-Methylcyclopropene (an ethylene inhibitor) could extend the shelf-life by delaying softening. The ethylene biosynthesis pathway involves Met (methionine), ACC2 (1-aminocyclopropane-1-carboxylic acid), SAM1 (S-adenosine methionine), and ethylene. ACS3 produces ACC from SAM, which is then converted to ethylene by ACO4 (Fig 1) (Van de Poel *et al.*, 2012). During biosynthesis pathway of ethylene, SAM is a key

precursor. Kiwifruit post-harvest ripening is associated with the expression of AcSAM1 and AcSAM2 (ripening genes), which are amplified by propylene treatment. In ethylene synthesis pathway, rate-limiting enzymes are ACO and ACS (Gan *et al.*, 2021). LeACO1 and LeACS2 expression blocking in tomatoes markedly postpones the ripening of fruits (Wilkinson *et al.*, 1995). Among the 54 ACO and 13 ACS genes in kiwifruit, ACO1, ACO2, ACS1, and ACS2 exhibited a substantial increase in expression due to ethylene during postharvest ripening (McAtee *et al.*, 2015). The expression of both senescence-associated genes (MaSAG1) and ethylene synthesis genes (MaACO1 and MaACS1) in banana fruits were governed by MaWRKY31 (Fan *et al.*, 2017). The kiwifruit genome contains 97 WRKY genes, and the administration of ethylene results in the heightened expression of AcWRKY38, AcWRKY40, and AcWRKY75 (Jing and Liu, 2018). AcWRKY40 gene expresses while kiwifruit postharvest ripening and is influenced by ethylene treatment. After genetic modification and qRT-PCR validation, it has been shown to potentially delaying the postharvest ripening (Gan *et al*., 2021).

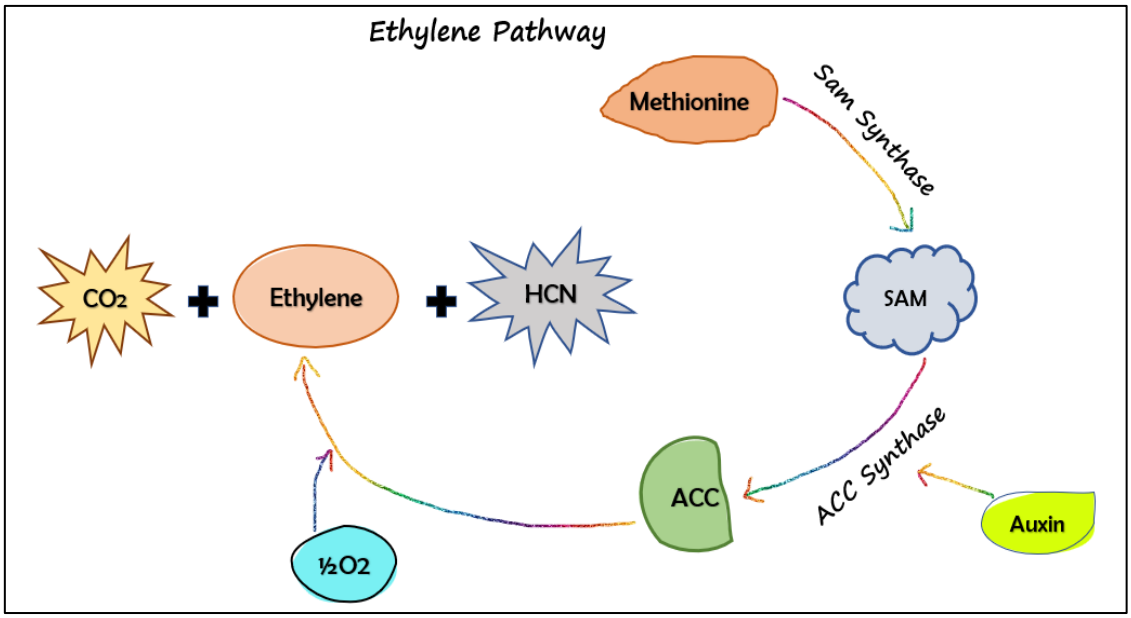

Fig 1: Ethylene biosynthesis pathway

2.1. Maturation of kiwifruit

Kiwifruits are typically harvested unripen but at maturity stage, to maintain commercial value during the cold storage (Burdon, 2018). Detailed studies of the fruit maturation biology may enhance the accuracy of fruit categorization during harvest. This understanding may extend beyond physiological composition, shedding light on various stages of fruit growth. Kiwifruit, for instance, has been the subject of research on non-structural carbohydrates. Findings indicate that certain enzymes, such as APL4 (ADP-glucose pyrophosphorylase), SPS4 (sucrose phosphate synthase), BAM3.2 (β-amylase), and SWEET9a (a sugar transporter), play a role in regulating starch breakdown, synthesis, and sucrose production (Gunaseelan *et al.*, 2019). Likewise, stay-green protein (*SGR2*) has been used to study pheophorbide a oxygenase (*PAO1*), pheophytin pheophorbide hydrolase (*PPH1*), chlorophyll breakdown and red chlorophyll catabolite reductase (*RCCR1) (Montefiori et al., 2016).* Fruit softening is also associated with a variety of genes under investigation. These include XYLOGLUCAN ENDO TRANSGLYCOSYLASE/HYDROLASE (XTH, β-GALACTOSIDASE), β-GALACTOSE (β-GAL), POLYGALACTURONASE (PG) and PECTATE/PECTIN LYASES (PL) *(Fullerton et al., 2020).* Ethylene receptors, response genes (including *ER, EIN3/EIL, CTR*), Ethylene metabolism and *ACO* (ACC oxidase) and (ACC synthase) *ACS* were also documented (McAtee *et al*., 2015). Moreover, MADS genes (McAtee *et al*., 2015) and NAC (transcriptional factors) (Mitalo *et al.*, 2019) are also related with kiwifruit ripening. The study aimed to investigate the transcriptional changes in 2 kiwifruit cultivars, *A. chinensis* (var. *deliciosa* Hayward) and *A. chinensis* (var. *chinesis* Zesy002) during maturation. The study was conducted by monitoring weekly changes in gene expression, focusing on commercially important cultivars grown in a single location in New Zealand. The study involved monitoring the gene expression changes in *A. chinensis* (var. *deliciosa* Hayward) and *A. chinensis* (var. *chinesis* Zesy002) during maturation, both before and after commercial harvesting. The results of the study indicated that 'Zesy002' matures earlier than 'Hayward', leading to differences in the commercial maturity period. The gene expression changes observed in the study included alterations in non-structural carbohydrates such as SWEET9a (sugar transporter), APL4 (large sub-unit 4 of ADP-glucose pyrophosphorylase) indicating starch synthesis, and BAM3.2 (BETA AMYLASE 3.2)

responsible for starch breakdown. Although Hayward and Zesy002 both varieties eventually showed similar levels of flesh degreening, the correlation between the degreening process and the STAYGREEN2 (SGR2) gene was more significant in Zesy002. Several changes in individual cell wall genes, such as XYLOGLUCAN TRANSGLYCOSYLASE/HYDROLASE (XTH), PECTIN METHYL EXPANSIN7 (EXP7), PECTATE LYASE (PL), ESTERASE (PME) and POLYGALACTURONASE1 (PG1) were linked to the rapid softening in 'Zesy002' *(Fullerton et al., 2020).*

Although EXP7 and PG1 genes displayed similar changes in 'Hayward', they had no significant effect on the rate of softening. During maturation the change of seed coat from green to yellow color, ripening initiation and growth inhibition are characterized by rapid softening and starch breakdown (Burdon *et al.*, 2021). Various patterns can be used to assess fruit maturity, such as differences in transcript abundance and timing between cultivars, which may be linked to significant composition changes. Another approach is to compare the rate of transcript level changes over time between cultivars. The most effective way to molecularly characterize maturation is to identify the sequential division of transcriptional changes within each cultivar, which is closely linked with a critical characteristic of fruit maturation.

3. Postharvest handling

Mechanical damage while postharvest handling is fruits is still a big challenge according to the FAO (Food and Agriculture Organization) (Gennari *et al.*, 2019). Harvest and post-harvest processes can cause mechanical damage to fruits, which can affect their quality and quantity. To minimize fruit waste, researchers have explored ways to optimize agricultural machinery and food processing systems. For kiwifruit (Actinidia spp.), understanding the changes in fruit quality can help develop effective processing and management strategies to reduce losses. Kiwifruit has a great economic value that is typically harvested unripen but physiologically mature (Goldberg *et al.*, 2021). After harvest respiration rate of kiwifruit naturally rises quickly within a few weeks, as a result ripening process triggers, fruit starts deteriorating rapidly and shelf life confines to just 3–4 days (Tilahun *et al.*, 2020). Kiwifruit contains starch as a reserve carbohydrate, which undergoes significant changes during ripening. The hydrolysis of starch leads to a significant increase in soluble solid concentration (SSC). Hence, establishing a standard for ripeness based on the starch content can be highly beneficial. The iodine test is a quick and accurate method used to determine the starch content of kiwifruit in production. Starch dyeing is extensively used to visually evaluate apple ripeness (Bonora *et al.*, 2021). The methods to detect SSC, starch content and firmness are actually destructive. Researchers have examined numerous nondestructive approaches to determine fruit ripeness including spectroscopy (Zhang *et al.*, 2020), electronic nose (Bonora *et al*., 2021), acoustic vibration (Landahl and Terry, 2020), spectral imaging (Nie *et al.*, 2020) and microwave (Redzwan *et al.*, 2018). In recent 5 years the use of acoustic vibration to govern fruit ripeness has been increased. (Minas *et al.*, 2021) assessed the Hayward's ripeness degree, using Vis/NIR spectroscopy (400–1000 nm). The classification sensitivity values of the model in this research were 97% and 93% for SCC and flesh firmness classes, respectively (Tian *et al.*, 2023).

To cope with more fragile fruit, such as 'Hort16A', which has a 'beak' at its distal end which may cause harm when it comes into touch with other fruit, these enormous handling systems must be made gentler (Liu *et al.*, 2021). When transported on moving belts or rollers, the fruit is subject to less forceful contact and is less likely to be damaged than if it were permitted to move freely. Belts transport the fruit, reducing the chance of damage, while rollers do the singulation, or separation of each piece for size grading. Drop heights less than 30 centimeters, flexible flaps to limit fruit velocity, and soft materials to absorb impact energy upon contact with equipment significantly minimize the danger of injury in areas when the fruit is not being transported. Handling highly influences the fruit hardness. For bulk storage in bins or grading line processing without compression or impact damage, fruit must be between 2.5 and 3.0 kgf firmness (Burdon and Lallu, 2011).

3.1. Reduce the Wound

Kiwifruit is perishable and sensitive to wounds. It can quickly deteriorate due to various mechanical injuries that occur during processing, such as cutting, slicing, and peeling. Additionally, during transportation and packaging, the fruit may become wounded and injured, leading to increased ethylene production and respiration that can seriously impact the fruit's quality and firmness. Research has proved that wounding typically causes a faster respiration rate and increased production of ethylene (Watada *et al.*, 1996). It has also been proven that ethylene and CO_2 production is enhanced by peeling and slicing of kiwifruit (Agar *et al.*, 1999). During the storage of kiwifruit, softening due to the wounds is also a major issue. The firmness of freshly cut fruit is one of the most important factors in determining its marketability (Mastrocola *et al.*, 1996).

Kiwifruit is sensitive to ethylene due to which it undergoes climacteric ripening, even at low levels (0.005-0.01 µl l−1). Higher ethylene production results in premature ripening and flesh softening, making it difficult to store it in cold storage for an extended perod (Crisosto *et al.*, 2000). 1-methylcyclopropene (1-MCP) at a concentration of 0.5-5.0 µl l−1 has dramatic effects in preserving kiwifruit's quality even after storing in cold storage for 30 days (Boquete *et al.*, 2004). After treating *Actinidia deliciosa* cv. Hayward halves with 1 µl l−1 of 1-MCP (1-methylcyclopropene), they were stored at 2°C

for 10 days. Several parameters such as total soluble solids (TSS), color, ethylene production, firmness, respiration rate, and electrolyte leakage, were measured after storage (Boquete *et al*., 2004). Wounding was observed to increase ethylene production and respiration rate in kiwifruit, which initiates ripening and causes softening, higher SSC, and electrolyte leakage. However, treating the fruit with 1-MCP (1 µl l−1) resulted in slower ethylene production, delayed softening, lowered respiration and electrolyte leakage, and less color deterioration. Applying 1-MCP prior to cutting has been shown to reduce ethylene production (Huan *et al.*, 2020). The findings suggest that 1-MCP treatment in kiwifruit prolongs the shelf life and enhances its resistance to physical damage (Mao *et al.*, 2007).

3.2. Pre-storage treatment

Fruit maturation and ripening process is genetically programmed and involves a range of complex metabolic processes, including flesh softening, aroma and flavor development and pigment accumulation characteristics (Kou *et al.*, 2021). As key physiological phases during postharvest ripening of kiwifruit, four distinct events of softening have been identified (Atkinson *et al.*, 2011). As fruits begin to ripe, they undergo a process where starch, an essential storage carbohydrate, is typically broken down. Kiwifruit, which is considered fully mature for commercial purposes, has around 40% of its dry matter in the form of starch, which can be transformed into soluble sugars with the ripening (Hu *et al.*, 2016). The deprivation of cell-wall components, that primarily contains cellulose, pectin, and hemicelluloses, is interceded by various (cell-wall-modifying) CWM enzymes like PL (pectate lyase), PG (polygalacturonase), and PME (pectin methyl esterase). Neutral sugars loss, decrease in firmness, depolymerization and solubilization of polysaccharides are some of the changes that occur during this process (Wang *et al.*, 2021a). That's why kiwifruit must be subjected to pre-storage treatments before keeping the in cold storage.

3.2.1 Short-term hypobaric pre-storage treatment

Kiwifruit is sensitive to low temperature and susceptible to chilling injury when stored for long time (Mworia *et al.*, 2012). Previous studies has specified that in modified atmosphere packaging, storage temperature, CO2 and O2 concentrations has a great impact in reducing the chilling injury in kiwifruit (Goldberg *et al.*, 2017). The kiwifruit storage industry is adopting the use hypobaric storage or controlled atmosphere combined with low temperature storage in recent years (Boukouvalas and Chouliras, 2005). SHT (short-term hypobaric treatment) is a pre-storage technique during postharvest handling in which fruit is exposed to sub-atmospheric pressure for a brief period, instead of hypobaric storage. This aims to extend the fruit's shelf life and reduce spoilage (Zheng, 2018). Kiwifruit "Hayward" was treated with potassium permanganate and subjected to a hypobaric atmosphere of (0.26 atm) 200 mmHg for 6 hours. When stored at 20°C, this treatment significantly extended their shelf-life (Ramin *et al.*, 2009). 'Taishan No.1' is a popular high-yield kiwifruit cultivar in Shandong province known for its strong cold resistance, despite having green skin and flesh. However, during the cold storage it is susceptible to chilling injury. To address this issue, harvested 'Taishan No.1' kiwifruits underwent a 15-hour treatment at 0.15 atm and were then stored at 1.0±1.0°C in MAP (modified atmosphere packaging) with 90% relative humidity (RH) for three months. Qualitative traits such as appearance, SSC, TA, decay rate, and firmness were assessed after cold storage and a subsequent shelf-life period at 20°C. The results indicated that the use of SHT with MAP was effective in reducing chilling injury and decay rate while increasing TA and firmness, and decreasing soluble solids content in kiwifruits. These findings suggest that SHT+MAP can be an optimistic way to preserve the postharvest quality of kiwifruits (Zhang *et al.*, 2019). The utilization of this technology could potentially facilitate the storage and preservation of kiwifruit, offering benefits such as ease of operation, cost-effectiveness, and high efficiency.

3.2.2 Pre-cooling treatment

To delay softening and senescence of kiwifruits after harvest, a study exposed Actinidia chinensis cultivar Cuiyu and Actinidia deliciosa cultivars to pre-cooling treatments. The first treatment involved intermissive pre-cooling, which entailed 1 day of pre-cooling at 20℃ after 1 day of pre-cooling at 0℃, followed by storage at 0℃. The second treatment involved atmospheric temperature pre-cooling, which involved 2 days of pre-cooling at 20℃, followed by storage at 0℃. The control group was stored at 0℃ directly. All groups were stored at a cool temperature of 0.5℃ with 90-95% RH. The results illustrated that the pre-cooling treatment and atmospheric temperature had dramatic effects on shelf life of Cuiyu kiwifruit (CK). Flesh firmness (2.0 kg/cm2) and un-rotten fruit ratio (68.0%) were both higher than CK (1.5 kg/cm2, 60%) after 90 days of cold storage, whereas the ratio of softened fruit (54.0%) was lower than CK (62.0%). Intermissive pre-cooling treatment improved the long-term storage potential of Miliang-1 kiwifruit. Flesh hardness (1.7 kg/cm2) and un-rotten fruit ratio (70.0%) both increased after 60 days of cold storage, whereas the ratio of softened fruits (36.0%) remained same (Decui *et al.*, 2008).

3.2.3 Treatment with 1-MCP (Methylcyclopropene)

During log-term storage Hayward should be protected from softening as it is highly sensitive to ethylene. One effective way to achieve this is by using 1-Methylcyclopropene (1-MCP) as a pre-storage treatment. 1-MCP (1-Methylcyclopropene) inhibits ethylene action and can be applied to kiwifruit harvested at 6.5° to 9° Brix by treating them with 0.5 mu l/L 1-MCP for 24 hours, followed by storage at 0°C. Previous studies have shown that kiwifruit stored under these

conditions for 4, 10, and 20 weeks can be taken out of cold storage and kept on a shelf for 14 days at 20°C. Samples were evaluated at 0, 4, 8, and 14 days during the shelf-life period (Liu *et al.*, 2021). After seven days of shelf-life, taste panels were conducted, which disclosed that ASA or SSC levels (measured in degrees Brix) were not affected in 1-MCP treated kiwifruit. Research concluded that 1-MCP treatment reduced the softening at 6.5 degrees Brix in short-term storage and for long-term storage at 9 degrees Brix. Additionally, 1-MCP improved the quality of kiwifruit harvested at 9 degrees Brix by increasing its ascorbic acid levels and taste panel ratings. Thus 1-MCP treatment is recommended to enhance the storage life of high-quality kiwifruit harvested at 9 degrees Brix (Huang *et al.*, 2019).

4. Storage

4.1 Storage at low temperature

After harvesting, cold storage is the way to extend the shelf life of horticultural products. This method slowdowns ethylene production and respiration (two important metabolic and ripening processes) by exposing the fruits to low temperatures (Hertog *et al.*, 2004). Chilling injury hinders the ability to store horticultural products at low temperatures. Tropical crops are particularly susceptible to this type of harm (Hertog *et al*., 2004). Chilling injury refers to physiological issues that arise in horticultural products when they are stored at temperatures below freezing but still relatively low (Wang, 1990). According to (Burdon and Lallu, 2011) Chilling injury appears as a rough texture on the outer pericarp and the presence of wet patches on both outer & inner pericarp. Various postharvest methods to minimize chilling injury in kiwifruit have been used, chiefly by regulating temperature (Ma *et al.*, 2014).

A decrease in chilling injury was found in 'Hayward' kiwifruit as precooling time to 0°C increases (Lallu, 1995). Direct cooling of 'Hongyang' kiwifruits to 0°C after 80 days of storage and 5 days at 20°C resulted in a higher incidence of chilling injury (68%) compared to the gradual cooling over 6 days (37%). Hazards of chilling injury in fruit that is slowly cooled can be reduced through temperature management techniques i.e. acclimatization (low temperature conditioning). This effect may be attributed to the increased activities of antioxidant enzymes in the fruit. (Lallu, 1995) showed that gradually lowering the temperature of 'Hayward' kiwifruit to 0°C after precooling to 7.5°C resulted in a significant reduction in chilling injury. Moreover, subjecting the kiwifruit to a 3-day holding period at 12°C prior to low-temperature conditioning has proved to enhance antioxidant activity and reduce chilling injury (Yang *et al.*, 2013). Cold storage-induced chilling injury was previously mitigated through the process of curing, which involved exposure to ambient temperatures for a specific duration. (Lallu, 1995) also verified that the Chilling injury declines with longer exposure (maximum 7 days) to ambient temperatures before cold storage. Recently (Burdon *et al.*, 2017) showed that subjecting freshly harvested kiwifruit (Hayward) to non-chilling temperatures of 16°C for 4-6 days resulted in firmer fruit during subsequent storage at 0°C, as such exposure is known to ameliorate low temperature breakdown. Storage experiments revealed that 'Hayward' kiwifruit stored for 24 weeks at 2.5°C did not exhibit chilling injury, in contrast more than 85% of fruit stored for the same duration at -0.5°C, showed symptoms. However, the softening of the flesh may hasten by storing fruit at higher temperatures (Schotsmans *et al.*, 2008). The feasibility of a temperature profile for kiwifruit storage that can improve firmness retention and decrease the likelihood of chilling injury through temperature switching was evaluated using a dual temperature storage approach. This involved temperature alternation between 0°C and 2°C at varying intervals during storage, and was studied to enhance storage quality and chilling injury for two important New Zealand kiwifruit cultivars, 'Zesy002' & 'Hayward'. Dual temperature treatments were employed to investigate their effects on kiwifruit of varying maturity levels, including 'Hayward' and 'Zesy002'.

The fruit was subjected to alternating temperatures of 0°C and 2°C during storage, with 'Hayward' exhibiting reduced softness and lower possibility of chilling injury when the storage began at 0°C and transitioned to 2°C. In contrast, 'Zesy002' demonstrated greater tolerance to chilling injury than 'Hayward', which was influenced by the maturity level of the fruit at harvest. Moreover, 'Hayward' kiwifruit stored at 0°C showed decreased firmness after 150 days, while such a trend was absent in the dual temperature treatments. Chilling injury incidence was observed to be correlated positively with the proportion of soft fruit. While temperature switching from 0°C to 2°C during storage resulted in improved storage life and reduced chilling injury incidence in 'Hayward' kiwifruit, such effects were not observed in 'Zesy002'. Moreover, the occurrence of chilling injury increased with a higher proportion of soft fruit (Schotsmans *et al*., 2008). This research suggests preserving 'Hayward' kiwifruit at 0°C for 50-125 days, then switching to 2°C, to improve postharvest quality. As fruit maturity affects chilling injury development and softening, future studies may use different temperature combinations (like 0 and 1°C) and kiwifruit of different maturity levels (Gwanpua *et al.*, 2018).

4.2. Ethylene Production

Kiwifruit is a climacteric fruit and ethylene production highly affects the rate of ripening. As ethylene levels rise during ripening, respiration also increases, leading to softening and changes in quality. Limiting ethylene production and respiration rates is crucial for maintaining fruit quality and extending postharvest storage (Kumarihami *et al.*, 2022). Studies show that the concentration of ethylene slowly increases during the first two months of storage for 'Hayward'

kiwifruit at 0°C, but then quickly hastens to approach the climacteric peak (Chiaramonti and Barboni, 2010). Kiwifruit exhibits a pattern of non-synchronous variation in firmness, ethylene emission, and entire quality of fruit (Kim *et al.*, 1999). Four distinct phases characterize the ripening during postharvest life of kiwifruit. Phase I involves maintenance of firmness and gradual softening after harvest. Phase II is characterized by a progressive loss of firmness, alterations in quality parameters, and color change without the production of ethylene. Phase III marks the onset of the "eating window", where the fruit becomes softer and develops characteristic aromas, coinciding with an increase in ethylene emission. Fruit enters the overripe stage during phase IV, which is marked by an unpleasant smell and flavor (Fig 2) (Atkinson *et al*., 2011). As a result, kiwifruit obtains an pleasing taste and an appealing flavor (Wang *et al.*, 2011).

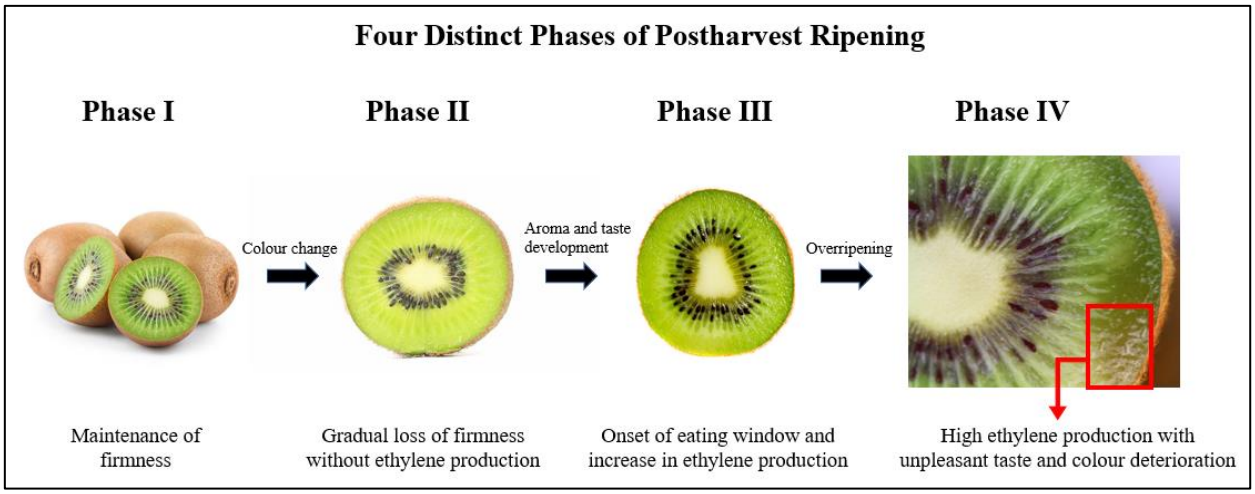

Fig 2: Illustrates the four distinct phases characterizing the postharvest ripening of kiwifruit

Depending on the variety and ripening stage, kiwifruit's taste varies (Garcia *et al.*, 2013). *Actinidia chinensis* var. *deliciosa* (green-fleshed kiwifruit) develops a sweet-tangy flavor with discrete notes of melon with green citrus, while *A. chinensis* var. *chinensis* (yellow-fleshed) exhibits a tropical profile of flavor with clues of berry fruit and mango (Jaeger *et al.*, 2003). Hort16A offers sweet aromas of blackcurrant and banana (Jaeger *et al*., 2003). In contrast, Hayward has been characterized as possessing a verdant odor with hints of the tropics (Friel *et al.*, 2007). As fruits mature, aldehydes (primary volatile organic compounds) are responsible for fresh, green, and grassy notes. But, when the fruit is ready to eat, esters take over as the main volatile organic compounds, imparting sweetness and fruity notes (Wan *et al.*, 1999). Transgenic kiwifruit having reduced ACO enzyme production did not produce ethylene and had less volatile production, which halted the softening process and extended the time frame for consumption. However, using 1-MCP to inhibit ethylene production also lowered the volatile esters, negatively impacting the fruit's quality (Chai *et al.*, 2021).

4.3. Green Preservation

Kiwifruit (Actinidia deliciosa) is highly nutritious and popular for consumption. Recently, the demand for its green preservation has been increased, fresh keeping. In this context wide applications of ozone have been observed. Ozone has been widely used to preserve its green color and freshness, due to its ability to delay ripening. Ozone achieves this by directly oxidizing ethylene, which is its primary mechanism of preventing ripening (Martínez-Romero *et al.*, 2007). Due to its sensitivity to ethylene, ozone has been extensively utilized for kiwifruit preservation during storage (Yin *et al.*, 2008), In addition to cold storage, ozone has been shown to be effective in preventing spoilage caused by *Botrytis cinerea*. Additionally, it can significantly impact plant cell metabolism (Tonneijck and Leone, 1993). New research have demonstrated that during cold storage ozone exposure can directly affect the green preservation of kiwifruit, even after it's taken out of the ozone-enriched environment. (Minas *et al.*, 2012),

This suggests that ozone directly influences the ripening of kiwifruit. Kiwifruit's cell wall undergoes significant dismantling, with rapid solubilization of cross-linking and pectic glycans. This results in a substantial increase in viscosity of cell wall texture (Schroder and Atkinson, 2006). RG-I-type pectins extensively removes Galactose, resulting in their loss. β-galactosidase (β-gal) enzyme has a major role in swelling and softening of kiwifruit cell walls (Ross *et al.*, 1993), This function wasn't always fully supported, though (Redgwell *et al.*, 1992). Ozone's effects on kiwifruit post-storage ripening and ethylene biosynthesis pathway components were examined to see whether it influences fruit physiology beyond ethylene oxidation. Additionally, the effect of ozone on degrading enzymes and cell wall polysaccharides was also examined to understand it's impact on kiwifruit ripening by storing *Actinidia deliciosa* cv. 'Hayward' in low ethylene conditions at 0°C (95% RH). The fruits were exposed to either air (control) or ozone (0.3 µL L−1) for 2 or 4

months, followed by up to 8 days of ripening at 20°C (90% RH). The maintenance of kiwifruit treated with ozone at 20 °C dramatically postponed the ripening. This was observed together with a considerable suspension in the production of ethylene, which was attributed to the downregulation of ACO & ACS enzymes along with AdACS1 and AdACO1 gene expression (Ilina *et al.*, 2010).

Furthermore, an obvious decrease in flesh softening and cell wall dismantlement was observed in ozone-treated fruits. The observed impact was linked to a decrease in cell wall swelling, as well as a reduction in the solubilization of pectin and neutral sugars. This effect was found to be connected with the suppression of cell wall degrading enzymes activities, specifically PG (polygalacturonase), endo-1, EGase/glu (4-β-glucanase/1,4-β-glucosidase) (Minas *et al.*, 2014). In conclusion, the study suggests that ozone has significant residual effects on the ripening physiology, freshness, and preservation of greenness in kiwifruit. The findings also indicate that ozone targets ethylene biosynthesis and cell wall turnover in particular.

4.4. Postharvest pathology

Kiwifruit is a widely cultivated and increasingly popular crop globally. However, the industry is suffering with huge losses while transportation, storage and local sales due to postharvest fungal rots. The Food and Agriculture Organization (FAO) estimated, in 2020 global kiwifruit yield reached 6.6 million tons, with New Zealand contributing more than 0.6 million tons (Azizi *et al.*, 2022). Regrettably, the increase in commercial kiwifruit production has led to a rise in the prevalence and severity of different fungal diseases, which could harm the industry. Kiwifruit postharvest fungal rot causes major economic losses during storage, transportation and marketing (Manning *et al*., 2016). Postharvest fungal pathogen *Botrytis cinerea* is a major threat to kiwifruit production. This issue is especially severe as crop area increases and extended storage times are required to satisfy customer demand for the fruit around the year (Michailides and Elmer, 2000). Moreover, *Alternaria alternata* & *Diaporthe spp.* are also some major pathogens of kiwifruit (Li *et al.*, 2017); (Díaz *et al.*, 2017).

4.4.1 Black rot and black spot disease

The kiwifruit is susceptible to black rot and black spot fungal diseases (Li *et al.*, 2018a). China identified the first incidence of black spot disease caused by *Nigrospora oryzae* (Yang *et al.*, 2021). He found that *Trichothecium roseum*, *Alternaria alternata*, *Diaporthe phaseolorum*, and *Cladosporium cladosporioides* are all capable of causing black spot disease during storage of 'CuiXiang' kiwifruit. In the infected fruit tissues hyphae at affected area damages mitochondria and reduces starch content. As a result, the shelf life of the fruit is significantly reduced. In Korea, *A. alternata* caused black spot in “Skinny Green” kiwifruit (Kwon *et al.*, 2011). Black spots develop around the calyx, gradually spreading and covering most of it, in black spot disease. The rot can penetrate the fruit's interior, and the lesion's exterior becomes hardened and mummified, making the infected fruits unsuitable for sale (Kwon *et al.*, 2017). *Candida oleophila* has demonstrated its efficacy as a biological control agent against *A. alternata*. Moreover, it has been observed to decrease the occurrence of natural decay (Wang *et al.*, 2018). *Hanseniaspora uvarum* yeast treatment enhances kiwifruit resistance against *A. alternata* by increasing the expression and activity of chitinase and β-1,3-glucanase genes & enzymes.

4.4.2 Blue mold

Blue mold, caused by the fungus *Penicillium expansum* is a major cause of postharvest loss in kiwifruit. The occurrence of postharvest decay in stored kiwifruit due to P. expansum was first reported in China by (Luo *et al.*, 2019b). The peel structure of 'Qihong' and 'Hongyang' kiwifruits was examined after inoculation of *P. expansum* to compare their resistance against the fungus. Results showed that 'Hongyang' kiwifruit exhibited stronger biochemical resistance due to higher levels of PAL (phenylalanine ammonia lyase) and POD (peroxidase) activity, as well as higher contents of total phenols, flavonoids, and lignin compared to 'Qihong' kiwifruit. Kiwifruit might get infected with *P. expansum* through lesions suffered during harvesting or handling, as well as via other primary fruit pathogens' infection sites, and overripe or long-stored kiwifruit (Prodromou *et al.*, 2018). *P. expansum* infection can lead to fruit flesh softening, rotting, and development of a pungent musty flavor. Furthermore, the fungus can generate patulin (harmful secondary metabolite for food security) (Mahunu *et al.*, 2018). The efficacy of chitosan as a biological control against blue mold (*P. expansum*) was demonstrated. 5 g/L chitosan inhibited P. expansum in 25 °C and 4 °C kiwifruit. Moreover, the gene expression & enzyme activity of catalase (CAT), superoxide dismutase (SOD), and ascorbate peroxidase were enhanced by chitosan treatment, as a result fruit quality was improved (Zheng *et al.*, 2017). Another way to deal with blue mold is treatment via ozone. (Luo *et al.*, 2019a) stated that O^3 treatment at 0°C for 7 days reduced disease rate and inhibited *P. expansum* growth in kiwifruit. Titratable acidity and firmness were maintained, and defense-related enzyme activity was enhanced.

4.4.3 Soft rot

During early postharvest ripening stages, *B. dothidea* may cause soft rot in kiwifruit stored at room temperature. This pathogen poses a significant threat to kiwifruit production worldwide, as it can infect various crop species. *B. dothidea* is most common pathogen in causing soft rot in China (Zhou *et al.*, 2015) and Korea (Koh *et al.*, 2003). Brown skin at the stem end or centre of kiwifruit indicates soft rot, with the affected areas having soft tissues underneath. In severe instances, the whole fruit might turn brown, with spoiling and unorganized inner tissues with a musty, wet odor (Wang

et al., 2021c). *A. alternata* is another fungus that causes soft rot in kiwifruit *(Li et al., 2021). Nigrospora sphaerica was also found in spreading the same disease(Li et al., 2018b).* Botryosphaeria dothidea is a pathogen that affects plants and can lead to various symptoms such as cankers, sunken areas, dieback, stem blight, and fruit rot. In some cases, it can even cause kiwifruit plants to die (Wang and Zhang, 2019). To see the comparison between resistant and susceptible kiwifruit host responses to *B. dothidea* contamination (Wang *et al.*, 2020) directed an RNA-seq analysis. Including DEGs involved in MAPK and PRRs 2,373 genes were identified. Modifications in the cell wall, transcription factor modulation, hormone metabolism, and calcium signaling were also analyzed. Moreover, more than 30 candidate genes for plant defense response were identified. Recently, researchers have been exploring various non-toxic natural compounds that can prevent soft rot in kiwifruit by inducing fruit resistance or employing antifungal mechanisms i.e. curcumin (Kai *et al.*, 2020) and methyl jasmonate (Pan *et al.*, 2020).

Natamycin, produced by Streptomyces natalensis, is a natural antimicrobial that effectively inhibits mold and yeast, making it a widely accepted food preservative. Its low toxicity to humans has led to its recognition as a GRAS (generally regarded as safe) product by the FDA. Additionally, it has been registered as a postharvest fungicide in the United States, exempt from residue tolerance (Saito *et al.*, 2022). This study investigated the inhibitory effects and mechanisms of natamycin against B. dothidea-induced soft rot. Results showed that 2 mg L−1 natamycin efficiently inhibited the growth and spore germination of *B. dothidea* in vitro. SEM and TEM images revealed that natamycin caused hyphal shrinkage, deformation, vacuolation, and plasmolysis. Furthermore, natamycin increased the accumulation of ROS in the hypha. Natamycin showed dose-dependent inhibition against B. dothidea in kiwifruit, with 500 mg L−1 reducing soft rot incidence to 35%.

Additionally, natamycin induced disease resistance in kiwifruit by activating antioxidant enzymes (SOD and CAT), increasing total phenol, lowering MDA levels, and suppressing the activity of four cell wall degrading enzymes. Furthermore, it repressed the gene expression of β-Gal and PG (Pan *et al.*, 2022). Natamycin was found to inhibit the growth and germination of B. dothidea, as well as cause oxidative damage to the hypha. It also activated antioxidant enzymes (SOD and CAT) and increased total phenol, while maintaining low levels of MDA. Additionally, it repressed the activity of cell wall degrading enzymes (β-Gal, PG, PME, and PL) in postharvest kiwifruit. These findings suggest that natamycin could be an effective strategy for controlling soft rot in kiwifruit. Some of other pathogens and their biological controls are shown below in the table 1.

Table 1: Kiwifruit pathogens and their biological controls

Kiwifruit Cultivar	Pathogen	Disease	Treatment	Effect on cultivar quality	References
A.deliciosa cv. Hayward	*P. expansum and Botrytis cinerea*	Blue & gray mold	Ozone	Disease frequency along with spore germination and inhibition of mycelial development was decreased. The TA and firmness of the fruit were sustained, while defense-related enzyme activity was enhanced.	(Luo *et al.*, 2019a)
A.chinensis	*Colletotrichum acutatum*	*Colletotrichum* rot	Cinnamon essential oil	Repressed spore germination and mycelial growth.	(He *et al.*, 2018)
A.*deliciosa*	*B. cinerea*	Gray mold	Volatiles of 'Isabella' Grapes	Restricted the rate of infection	(Kulakiotu *et al.*, 2004)
Actinidia chinensis cv. Hongyang	*Alternaria alternata and Botrytis cinerea*	Black rot, gray mold	*Candida oleophila* and oligogalacturonide	Induced defensive enzymes activity and gene expression.	(Gao *et al.*, 2021)
A.*chinensis* cv. Hongyang	*Botrytis cinerea* and *P. expansum*	Blue &, gray mold	Harpin and *Candida diversa*	Decreased the blue and gray mold, and improved the efficiency of SOD, POD, and polyphenol oxidase.	(Tang *et al.*, 2015)
A.deliciosa cv. Hayward	*B. cinerea*	stem-end rot	Ozone	The presence of ozone inhibited the development of mycelium and prevented the pathogen from sporulating.	(Sui *et al.*, 2020)
A.*deliciosa* cv. Jinkui	*B. dothidea*	Soft rot	Methyl jasmonate	Enhanced the activity of defensive enzymes and the total phenolic content. Reduces lesion diameter	(Pan *et al.*, 2020)

CONCLUSION AND FUTURE PERSPECTIVE

Ensuring the postharvest quality and extending the storage time of kiwifruit is a crucial challenge for the kiwifruit industry. Proper storage techniques are essential to prevent rapid decay and softening of this climacteric fruit. This article has focused on four key perspectives: scientific harvesting, green preservation, ethylene management, and low-temperature storage, as well as texture and quality. By exploring the advancements in these areas, it is concluded that harvesting of kiwifruit at 160 DAFB and 6.2°Brix possessed improved eating quality. AcWRKY40 gene is responsible for ethylene biosynthesis in kiwifruit and its downregulation can slow down the ripening process. 1-MCP application, ozone treatment, SHT and pre-cooling treatments were not only resulted in lowering ethylene production, delayed softening, lowered respiration and electrolyte leakage but also reduced the chances of postharvest pathology of kiwifruit. To fully utilize the available germplasm resources, a comprehensive understanding of reproductive biology is necessary. By integrating these research findings and leveraging the potential of germplasm resources, the kiwifruit industry can strive towards enhancing storage capacity and developing improved storage and preservation techniques. Ultimately, these advancements will contribute to the overall growth and success of the kiwifruit industry, ensuring the availability of high-quality kiwifruit for consumers worldwide. The future postharvest management for kiwifruit will present numerous challenges. An expanded variety of commercially available cultivars is expected, and their postharvest performance is likely to vary significantly from available varieties. Consequently, new approaches must be developed to optimize postharvest performance, particularly in managing temperature sensitivity and harvesting fruit to cater to specific market niches. In the laboratory, the focus of postharvest science will shift from merely describing the fruit's condition and attempting to correlate it with postharvest performance to identifying the factors that govern postharvest performance. This transition is already occurring through ongoing gene expression research and will be most effective when integrated with other scientific disciplines. Additionally, in packhouses, increased automation will decrease reliance on a diminishing or unwilling labor supply to fill certain positions.

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