



REVIEW ARTICLE

Recent advances in ripening-associated molecular mechanisms in mango

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Abstract

Mango (*Mangifera indica* L.) is a climacteric fruit and its ripening and post-harvest quality is regulated by complex interactions of genetic, hormonal, biochemical and molecular regulatory networks. Ethylene is a major regulator of fruit ripening, inducing 1-aminocyclopropane-1-carboxylic acid synthase (ACS) and ACC oxidase (ACO) which control processes associated with fruit ripening such as cell wall degradation, pigment accumulation, aroma production and sugar metabolism. Fruit quality is controlled by the interaction of ethylene with abscisic acid, jasmonic acid, salicylic acid and reactive oxygen species (ROS) pathways that regulate fruit maturation, antioxidant metabolism and defence responses. The main post-harvest pathogens *Colletotrichum gloeosporioides* and *Lasiodiplodia theobromae* utilise changes related to ripening to shift from latent infection to active disease development. Recent advances such as treatment with 1-methylcyclopropene, hexanal formulations, controlled atmosphere storage, etc., have shown potential to delay ripening, maintain antioxidant capacity and reduce post-harvest losses. New technologies such as clustered regularly interspaced short palindromic repeats (CRISPR/Cas) genome editing, RNA interference, multi-omics approaches and nanotechnology-based delivery systems are emerging opportunities that manipulate ripening and disease-resistance pathways. However, the balance between extending shelf-life and retaining flavour, consumer acceptance, biosafety and environmental sustainability remains to be addressed. Future research in transcriptomics, metabolomics, proteomics and epigenomics will be critical to identify molecular targets and develop precision-based strategies to improve mango shelf life, quality and resistance to post-harvest pathogens.

Keywords: ethylene; *Mangifera indica*; multi-omics; post-climacteric ripening; post-harvest quality; shelf life

Introduction

Mango (*Mangifera indica* L.), often acclaimed as the “King of Fruits,” is one of the most important tropical fruits cultivated globally owing to its exceptional organoleptic properties and nutritional value (1). In India, mango is grown extensively in 2.3 million hectares, with an annual production reaching approximately 20.72 Mt (2). The fruit encloses a single oblong seed embedded within juicy, aromatic pulp. Mango pulp is a rich source of provitamin A carotenoids, vitamin C, carbohydrates, organic acids and essential minerals, making it a vital dietary component in many tropical regions.

Historically, mango domestication and early cultivation originated in South and Southeast Asia and later expanded to all tropical and subtropical regions with favourable soil and climatic conditions. Despite its popularity and economic significance, mango is highly perishable due to its climacteric nature, characterised by a surge in respiration and ethylene production during ripening. This rapid physiological transition significantly limits its post-harvest life, resulting in 20–30 % annual losses during handling, storage and transportation (3). The ripening of mango is governed by a complex network of genetic, hormonal, enzymatic and transcriptional interactions that control fruit quality, shelf life and susceptibility to

post-harvest disease. Genetic ripening involves the coordinated expression of genes involved in the synthesis of ethylene [1-aminocyclopropane-1-carboxylic acid synthase (ACS), ACC oxidase (ACO)], breakdown of cell wall [polygalacturonase (PG), pectin methyl esterase (PME), pectate lyase (PL) and expansin (EXP)], accumulation of carotenoid, sugar metabolism and production of volatile aroma compounds, pigments such as anthocyanin and carotene in fruits (4–6). The hormonal layer is mainly controlled by ethylene, which interacts with abscisic acid (ABA), jasmonic acid (JA), salicylic acid (SA) and reactive oxygen species (ROS) to regulate ripening progression and stress responses (7, 8). These hormonal cues activate enzymatic pathways responsible for fruit softening, colour development, flavour formation and antioxidant metabolism, including PG, PME, PL, β -galactosidase and carotenoid biosynthetic enzymes (9). Together, these interconnected regulatory modules form the molecular framework associated with mango ripening, providing key targets for interventions aimed at balancing shelf-life extension, sensory quality retention and resistance to post-harvest pathogens.

Given the significant economic losses from post-harvest spoilage and the importance of maintaining fruit quality during distribution, there is a growing need to develop effective, sustainable

technologies for extending mango shelf life. This review compiles recent advances in understanding mango ripening physiology, the role of ethylene and the impact of post-harvest treatments, including chemical, hormonal and biotechnological approaches to delay senescence and thereby extend the shelf-life of fruits. It aims to provide insights to improve post-harvest handling and enhance the commercial value of mangoes.

Ripening studies in commercial cultivars of India

Ripening in mango is a complex physiological process involving coordinated changes in colour, texture, flavour and aroma, driven by ethylene biosynthesis and downstream transcriptional regulation. Commercial varieties, such as 'Alphonso', 'Dashehari', 'Langra', 'Banganapalli', 'Kesar' and 'Tommy Atkins' (native to the USA), have distinct ripening characteristics (Table 1). The cultivar Alphonso is characterised by its rich aroma, uniform ripening pattern and high β -carotene content. These desirable quality attributes are associated with a pronounced climacteric ethylene peak and elevated expression of the ethylene biosynthesis genes *MiACO* and *MiACS*, along with the production of a distinctive terpene profile that contributes to its characteristic flavour and aroma (10, 11). In contrast, Dashehari often displays uneven ripening and is susceptible to internal physiological disorders such as spongy tissue formation. This cultivar exhibits early sensitivity to ethylene, while reduced antioxidant activity has been linked to the occurrence of internal breakdown during ripening (12, 13). The cultivar Langra represents a green-ripe type mango that retains firmness even at advanced stages of ripening. Its ripening process is associated with a moderate ethylene response and delayed expression of cell wall-softening genes, resulting in slower textural changes compared with other cultivars (14). Similarly, 'Tommy Atkins', when cultivated under Indian conditions, demonstrates delayed ripening and prolonged firmness, traits that are associated with relatively low ethylene production and suppression of key components of the ethylene signalling pathway (15). These cultivar-specific differences highlight the complex interplay between hormonal regulation, gene expression and fruit quality attributes during mango ripening. 'Dashehari' is characterised by rapid ethylene evolution and high respiration rates, leading to faster ripening and reduced shelf life. In contrast, 'Totapuri', 'Amrapali' and 'Tommy Atkins' exhibit delayed ripening due to slower ethylene biosynthesis and lower respiratory activity (15). Shelf-stable cultivars such as Amrapali and Mallika exhibit reduced activity of PG and PME, thereby delaying softening (16). In addition, the presence of a thicker cuticle and higher wax content in cultivars like 'Tommy Atkins', 'Kent', 'Ataulfo' and 'Neelum' is related to reduced moisture loss and delayed shriveling in ambient conditions (17). Post-harvest life is further influenced by resistance to fungal pathogens; 'Totapuri' and 'Tommy Atkins'

exhibit moderate resistance to anthracnose and stem-end rot (18). Further, antioxidant-rich cultivars such as Tommy Atkins and Keitt demonstrate higher levels of ascorbic acid and phenolics, enhancing oxidative stress tolerance during storage (19).

Enzymatic drivers of climacteric ripening

Climacteric fruit ripening is a complex, genetically programmed process marked by a burst of ethylene production and a sharp increase in respiratory activity (Fig. 1). This transition initiates a cascade of biochemical changes that involve a suite of ripening-associated enzymes regulating crucial traits such as softening, flavour development, colour transformation and aroma biosynthesis, which influence post-harvest shelf life and consumer acceptance (20–23). One of the most prominent enzymatic changes involves cell wall-modifying enzymes, including PG, PME, β -galactosidase and EXP, which orchestrate the degradation of pectin and hemicellulose, leading to fruit softening (24). Concurrently, amylases and invertases catalyse the conversion of starch into simple sugars, enhancing sweetness (25). Colour development is governed by enzymes such as chlorophyllase and phytoene synthase (PSY), which mediate chlorophyll breakdown and carotenoid biosynthesis, respectively, driving the green-to-yellow or red transition (26). Volatile compound biosynthesis, essential for fruit aroma, is regulated by lipoxygenase (LOX), alcohol dehydrogenase (ADH) and alcohol acetyltransferase (AAT) (27).

1-aminocyclopropane-1-carboxylic acid (ACC) serves as the direct precursor in the production of ethylene in higher plants. The ACS catalyses the conversion of SAM to ACC, which is then oxidised to ethylene by ACO. Ethylene diffuses readily both within and between cells and receptors at the endoplasmic reticulum membrane detect it (28, 29). The transcription of ripening-related genes is triggered by ethylene sensing and signalling, which further increases the enzymatic activity across several pathways (30). During fruit ripening and post-harvest storage, the antioxidant system—which includes non-enzymatic substances like ascorbic acid, phenolics and flavonoids as well as enzymatic antioxidants like superoxide dismutase (SOD), catalase (CAT) and peroxidases (POD) preserve cellular integrity. Understanding the temporal and spatial regulation of these enzymes offers valuable targets and strategies for improving shelf-life.

Post-harvest technologies, such as 1-methylcyclopropene (1-MCP), hexanal formulations, controlled atmosphere storage, edible coatings (chitosan, *Aloe vera*, xanthan gum) and treatments with SA, melatonin, nitric oxide, or 6-benzyladenine, are widely used to delay ethylene-mediated ripening, reduce respiration and softening and suppress post-harvest diseases (31). Emerging molecular interventions such as RNA interference (RNAi) and CRISPR/Cas

Table 1. Ripening characteristics of Indian mango cultivars

Cultivar	Ripening characteristics	Hormonal regulation	Key molecular insights	References
Alphonso	Rich aroma, uniform ripening, high β -carotene	Sharp ethylene peak during climacteric rise	Elevated expression of <i>MiACO</i> and <i>MiACS</i> genes; distinct terpene profile	(8, 9)
Dashehari	Uneven ripening, internal breakdown common	Early ethylene sensitivity	Low antioxidant activity linked to spongy tissue	(10, 11)
Langra	Green-ripe type, firm texture retained	Moderate ethylene response	Delayed cell wall softening gene expression	(12)
Tommy Atkins (Indian grown)	Delayed ripening, firm fruit	Low ethylene production	Suppressed ethylene signaling components	(13)

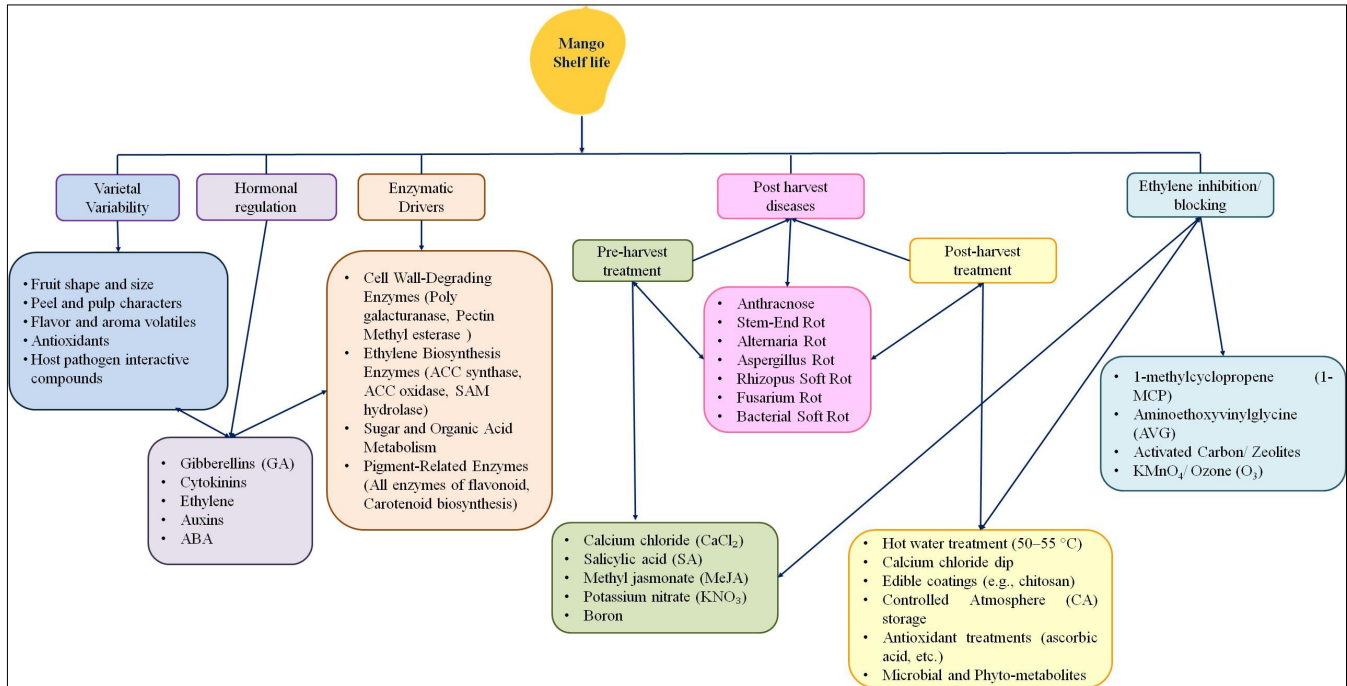


Fig. 1. Multi-layered regulation of mango shelf life and ripening: From ethylene signalling to pre and post-harvest treatments.

genome editing provide powerful tools to functionally validate and manipulate target genes involved in ethylene biosynthesis (*ACS*, *ACO*), cell wall degradation (*PG*, *PME*) and transcriptional regulation (*NAC*, *ERF*, *MADS-box*), offering challenges to extend shelf life while preserving fruit quality. More recently, nanotechnology-based delivery systems and nanoparticle coatings have been explored to enhance antimicrobial protection and targeted delivery of bioactive compounds. Together, these approaches bridge fundamental ripening biology with practical post-harvest management and represent key avenues for developing next-generation mango varieties and storage technologies.

Post-harvest disease resistance and ripening

Post-harvest disease resistance plays a pivotal role in determining the marketability and storage potential of mango cultivars (32). The most prevalent post-harvest diseases affecting mango are listed in Table 2. The genetic basis of disease resistance in mango is complex and includes the activation of defence-related genes, phenolic metabolism and structural barriers like cuticular thickness. Resistant cultivars typically show elevated expression of pathogenesis-related

(PR) proteins, higher antioxidant enzyme activity and slower pathogen colonisation post-harvest (33). The inter-relationship between the post-harvest pathogen infection and ripening processes of mango and other climactic fruits involves a highly regulated mechanism that involves hormones, remodelling of cell walls, oxidation and defence signals. Post-harvest pathogens like *Colletotrichum gloeosporioides* (anthracnose) and *Lasiodiplodia theobromae* (stem-end rot) are known to cause quiescent infections and stay dormant up to the time of ripening (34–36). During the ripening period, there is an increase in the production of climacteric ethylene due to the activation of *ACS* and *ACO* genes. Ripening-related pathways are also activated due to climacteric ethylene leading to the softening of fruits, increased sugar content, development of colours and the formation of volatile compounds. There is also increased production of cell wall degradation enzymes like *PG*, *PME*, *PL*, β -galactosidase and expansins during ripening leading to reduced cell wall integrity and facilitating the entry of pathogens inside tissues. Similarly, cell wall degradation and ethylene signalling during ripening have increased the susceptibility of fruits to pathogens like *Botrytis cinerea*, *Colletotrichum* spp.,

Table 2. Post-harvest diseases of mango

Disease name	Causal organism	Symptoms	References
Anthracnose	<i>Colletotrichum gloeosporioides</i>	Black sunken spots that coalesce; skin cracks and fruit rots.	(17, 34)
Stem-end rot	<i>Lasiodiplodia theobromae</i> , <i>Diplodia</i> spp.	Soft rot from stem end inward, dark and shriveled.	(35, 36)
Alternaria rot	<i>Alternaria alternata</i>	Black or dark brown patches, fruit softening.	(37)
Aspergillus rot	<i>Aspergillus niger</i> , <i>A. flavus</i>	Moldy growth at injury sites, black or green colour.	(38)
Rhizopus soft rot	<i>Rhizopus stolonifer</i>	Rapid, watery decay with cottony growth.	(39)
Fusarium rot	<i>Fusarium</i> spp.	Internal rot, discolouration, sometimes pinkish mycelium.	(40)
Penicillium rot	<i>Penicillium</i> spp.	Blue/green mold on injured skin.	(41)
Phomopsis rot	<i>Phomopsis mangiferae</i>	Small black lesions expanding into soft rot.	(42, 43)
Cladosporium rot	<i>Cladosporium</i> spp.	Superficial black mold.	(44)
Sour rot	<i>Geotrichum candidum</i>	Watery soft rot with sour smell.	(44)
Bacterial Soft rot	<i>Erwinia carotovora</i> (now <i>Pectobacterium</i>)	Foul-smelling, watery rot.	(45)
Mucor rot	<i>Mucor</i> spp.	Soft, watery decay; fluffy white mycelium.	(46)

Monilinia fructicola and *Penicillium expansum* as given in Table 2 (37–49). Transcription factors regulating ripening, such as MADS-box (RIN), NAC, ERF and WRKY transcription factors, coordinate development with pathogenesis. It has been shown in tomatoes that the mutants of ripening genes like *RIN*, *NOR* and *CNR* lead to a change in sensitivity towards the fungal pathogens, emphasising the connection between ripening and disease process (50, 51). Transcriptome analysis has shown that the fungi pathogens utilise the ripening pathways of hosts by regulating ethylene signalling, pH regulation and carbohydrate metabolism to induce the switch from quiescence to necrotrophy (52, 53). Altogether, results from mango fruits and other climacteric and non-climacteric fruits indicate that ripening and disease susceptibility are two connected processes and pathogenic success mainly relies on ripening physiology and molecular mechanisms.

Molecular and biotechnological advances

Advances in genomic technologies have elucidated the complex regulatory networks governing mango ripening, enabling precise interventions to extend shelf life. High-throughput sequencing and transcriptome profiling have identified genes involved in ethylene biosynthesis (*ACS*, *ACO*), signal transduction (ethylene receptors, ERFs) and cell wall modification (polygalacturonase, pectin methyl esterase) with cultivar-specific expression patterns linked to ripening rates. Multi-omics integration has further identified transcription factors, including MADS-box and ERF family members, which modulate stress responses and antioxidant pathways, directly affecting post-harvest quality and oxidative damage mitigation (54). These findings have been instrumental in developing molecular markers for breeding programs targeting enhanced storability. Despite progress, limitations remain in stable field-level translation due to genetic complexity, off-target effects and consumer acceptance. Integration of biotechnological tools with traditional breeding and optimised post-harvest treatments is imperative for commercial application. Fruit crops can benefit from advanced technologies like CRISPR/Cas genome editing, RNA interference (RNAi) and nanotechnology-based interventions to increase resistance to fungal diseases, prolong shelf life and improve post-harvest quality. In several horticultural crops, CRISPR-mediated alteration of ripening and susceptibility-associated genes, such as *ACS*, *ACO*, *PG*, *NOR* and *RIN*, has shown great promise for post-harvest loss reduction and fruit softening delay (55, 56). Similarly, RNAi-based strategies that target host susceptibility genes or pathogen virulence factors have demonstrated effectiveness in controlling ripening-related pathways and inhibiting fungal infection (57). Therefore, while CRISPR, RNAi and nanotechnology offer transformative opportunities for sustainable post-harvest disease management and shelf-life enhancement, their successful integration into commercial horticulture will require rigorous biosafety evaluations, harmonised regulatory frameworks, long-term environmental monitoring and effective public communication strategies to ensure both technological efficacy and societal acceptance (58, 59).

Recent advances in shelf life extension

To mitigate the rapid ripening and quality degradation, both Pre-harvest and post-harvest treatments targeting ethylene biosynthesis and signaling have gained attention. Chemicals such as silver nitrate, aminoethoxy-vinyl glycine (AVG), benzothiadiazole, sodium nitroprusside and cycloheximide have shown promise in delaying

ripening by inhibiting ethylene production or action (60). In addition, ethylene action inhibitors such as 1-methylcyclopropene (1-MCP) and various natural or nanomaterial-based treatments are being explored for their efficacy in shelf life enhancement.

Recent research has significantly advanced strategies for delaying mango ripening and preserving post-harvest quality of various cultivars. These have focused on innovative pre- and post-harvest applications, novel coatings and plant growth regulators (Fig. 1) (Table 3). Pre-harvest treatments such as SA (60), calcium salts [CaCl_2 , $\text{Ca}(\text{NO}_3)_2$] (61), potassium nitrate (62), gibberellic acid and ethylene inhibitors like 1-MCP (63) enhanced mango storability by strengthening cell walls and reducing physiological weight loss. 1-Methylcyclopropene which is a synthetic volatile cyclopropene derivative, represents a key ethylene receptor inhibitor in post-harvest physiology and plant stress resistance research. By competitively binding to ethylene receptors, 1-MCP effectively inhibits the ethylene signalling pathway, thereby delaying plant maturation, senescence and stress-induced physiological disorders.

Post-harvest interventions such as hot water treatment (64), calcium dips, edible coatings (65), controlled atmosphere storage (66) and antioxidant applications further suppress decay and oxidative stress, maintaining fruit firmness and quality. Together, these integrated strategies effectively extend mango shelf life and improve post-harvest quality for better marketability. These findings highlight the efficacy of targeted pre-harvest sprays in improving mango storability and post-harvest quality. Nanomaterials such as zinc oxide (ZnO), titanium dioxide (TiO_2), chitosan and silver nanoparticles have also been reported to enhance fruit storability through antimicrobial activity, improved barrier properties and induction of host defence responses (67, 68). Despite these technological advances, their commercial application remains limited by several regulatory, environmental and societal challenges.

While 1-MCP, hexanal, edible coatings and MAP currently provide the best balance between shelf life extension and market feasibility, treatments of melatonin, SA, nitric oxide and 6-BA show promising effects on antioxidant metabolism and disease resistance but require optimisation for commercial adoption. Further, CRISPR, RNAi and nanotechnology represent future solutions rather than current commercial practices. Development of a multi-criteria mango shelf life technology index (M-CMSTI) would provide a standardised framework for objectively comparing post-harvest interventions and identifying the optimal balance between storage life, sensory quality and disease resistance. This represents a valuable research opportunity for post-harvest mango.

Volatile and natural compounds, hormones, ethylene inhibitors and signal molecules

Recent studies demonstrate that natural compounds, ethylene inhibitors and signalling molecules effectively delay ripening and extend mango shelf life by regulating ethylene biosynthesis, maintaining membrane integrity, enhancing antioxidant defences and reducing pathogen incidence. Application of 6-benzylaminopurine (6-BA) effectively delayed ripening and senescence by suppressing respiration and ethylene production through inhibition of *ACS* and *ACO* activities (69). Furthermore, 6-BA downregulated phospholipase D (PLD) and lipoxygenase (LOX) activities and their related genes, preserving membrane integrity and limiting lipid peroxidation, thereby extending shelf life and maintaining fruit quality (69). Excessive reactive oxygen species

Table 3. Integrated pre-harvest and post-harvest strategies to enhance mango shelf life

Treatment type	Treatment / Compound	Mode of action	Effect on mango storability	Region / Country	Reference
Post-harvest	Antioxidant treatments (ascorbic acid, etc.)	Scavenge ROS, reduce oxidative damage	Delays browning and extends shelf life	Various	(18)
Pre-harvest	Salicylic acid (SA)	Enhances antioxidant activity, reduces ethylene	Delays senescence and reduces decay	India and Egypt	(60)
Pre-harvest	Calcium chloride (CaCl ₂)	Strengthens cell walls, reduces softening	Delays ripening, reduces fruit cracking and improves firmness	India, Egypt and Mexico	(61)
Post-harvest	Calcium chloride dip	Reinforces cell walls, delays softening	Maintains firmness and reduces decay	India and Egypt	(61)
Pre-harvest	Potassium nitrate (KNO ₃)	Enhances stress tolerance and metabolism	Delays senescence and reduces decay	India	(62)
Pre-harvest	1-Methylcyclopropene (1-MCP)	Blocks ethylene receptors, slows ripening	Extends firmness and delays colour change	USA and Israel	(63)
Post-harvest	1-Methylcyclopropene (1-MCP)	Ethylene action inhibitor	Extends firmness and delays ripening	USA and Israel	(63)
Post-harvest	Hot water treatment (50–55 °C)	Kills surface pathogens, induces stress tolerance	Controls anthracnose, stem-end rot and extends shelf life	India and Mexico	(64)
Post-harvest	Edible coatings (e.g., chitosan)	Creates semi-permeable barrier, reduces moisture loss	Maintains firmness and delays senescence	Australia and India	(65)
Post-harvest	Controlled Atmosphere (CA) storage	Low O ₂ , elevated CO ₂ suppress ethylene and respiration	Prolongs firmness and shelf life	Thailand and USA	(66)
Pre-harvest	Boron	Strengthens cell walls, improves membrane integrity	Improves firmness and reduces storage disorders	Thailand and India	(79)
Pre-harvest	Methyl jasmonate (MeJA)	Induces defense response, boosts antioxidant enzymes	Increases antioxidant content and delays ripening	China and India	(80)

(ROS) accumulation damages membranes and weakens pathogen resistance, facilitating infection by pathogens like *C. gloeosporioides*. Therefore, maintaining ethylene–ROS homeostasis through regulation of ethylene biosynthesis/signalling and antioxidant enzymes (SOD, CAT, APX and POD) is critical for delaying ripening and enhancing post-harvest disease resistance in mango. Hexanal, either as a post-harvest dip or as an enhanced freshness formulation (EFF), suppresses ethylene production, PLD, respiration and fruit decay while enhancing antioxidant enzyme activities (SOD, CAT, APX, GPX), resulting in delayed ripening and improved fruit quality (70). Pre-harvest application of EFF (1600 µM) has been identified as the optimum dose for extending storage life and reducing post-harvest losses in mango. Natural antioxidant-based coatings, such as xanthan gum enriched with pomegranate peel extract, further reduced weight loss, respiration and ethylene evolution while preserving firmness, acidity, ascorbic acid, phenolics and antioxidant capacity (71). Ethylene inhibition strategies, particularly 1-MCP, aminoethoxy vinyl glycine (AVG) and 2-aminooxyisobutyric acid (AOIB), effectively delay ripening by suppressing ethylene biosynthesis and signalling, although excessive inhibition may increase disease susceptibility in some cultivars (72, 73). Nitric oxide (NO) acts as a multifunctional signalling molecule that delays senescence by inhibiting ethylene production, strengthening antioxidant systems, regulating cell wall metabolism and interacting with other signalling pathways (74). Evidence from mango and other climacteric fruits such as plum, apple and lime confirms the broad applicability of these approaches in reducing physiological deterioration, maintaining quality attributes and significantly extending post-harvest shelf life (75). Collectively, these interventions provide promising, environmentally friendly strategies for improving

fruit storability, marketability and consumer acceptance. As environmental safety assessments are required to address potential off-target effects of various emerging technologies and the ecological consequences of nanoparticle accumulation in agricultural ecosystems (76), these remain key challenges for real world adoption. Nanoparticles raise concerns regarding persistence in soil and water systems, bioaccumulation in edible plant tissues and potential toxicity to beneficial microorganisms and human consumers.

A large meta-analysis of 1-MCP effects across climacteric fruits demonstrated that delaying ethylene perception consistently extends storage life, maintains firmness and slows ripening, but responses of aroma volatiles, flavour-related metabolites and overall eating quality vary considerably among species and storage conditions (77). Apple represents an example where this trade-off is a major research area in post-harvest physiology. Commercial use of 1-MCP even though dramatically reduces softening and extends storage for months, numerous studies report suppression of ester biosynthesis and aroma volatile production, resulting in fruit that remain firm but exhibit diminished characteristic apple flavour. Even though, 1-MCP and cold storage effectively delayed senescence and preserved firmness, it is accompanied by reduced aroma volatile accumulation and flavour perception when treatment intensity was too high (78). Other integrated Pre-harvest and post-harvest strategies to enhance mango shelf life are further documented in laboratory studies (79, 80). Studies on shelf life extension for identifying molecular targets that uncouple disease resistance from flavour loss, remains arguably the central unresolved problem in mango post-harvest biology.

Conclusion

The regulation of mango ripening and senescence is a multifaceted process governed by ethylene biosynthesis, hormonal cross-talk and intricate enzymatic and molecular networks. Considerable progress has been achieved in understanding these mechanisms, revealing cultivar-specific differences in ethylene evolution, enzyme activity and antioxidant potential that collectively define storability. Integrative post-harvest interventions ranging from calcium and salicylic acid (SA) applications to advanced treatments such as 1-MCP, nitric oxide, melatonin and nanoparticle-based edible coatings—have significantly improved firmness retention, delayed pigment and aroma development and reduced microbial decay. However, large-scale translation of these approaches remains constrained by cost, consumer perception and variable cultivar responses. In future, research should be focused on the analysis of different omics (transcriptomics, proteomics, metabolomics and epigenomics) to unravel the complicated interactions between genes and metabolites in the process of fruit softening and pathogenesis of diseases after harvesting. Though the modern packing and edible coating techniques have significantly decreased post-harvest losses and enhanced the quality of storage, their application in commercial scale has been limited due to the variable response of cultivars to environment, cost efficiency and regulations. The research, should be focused on knowledge gaps which can be tested, namely: (i) understanding the interactions in hierarchies of ripening regulators such as RIN, NOR, CNR, AP2a and NAC transcription factors in mango; (ii) understanding the molecular switch which controls the transition from latent to necrotrophic stage in pathogens during ripening process; (iii) studying the crosstalk in the processes of ethylene, abscisic acid, jasmonic acid, SA and reactive oxygen species signalling under post-harvest conditions; (iv) revealing the contribution of different epigenetic modifications (DNA methylation, chromatin modification) into shelf life and disease resistance. Translational research can use molecular targets which show the impact on ripening and susceptibility to the disease as priority candidates for genetic improvements. The comparative analyses across climacteric and non-climacteric fruit species are needed to identify conserved regulatory modules that can serve as universal targets for post-harvest quality enhancement. Addressing these priorities will enable the development of predictive, mechanism-based strategies for extending shelf life, preserving nutritional quality and minimising post-harvest losses in fruit crops under commercial supply chains.

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Authors' contributions

AT prepared the manuscript. AB conceptualised, structured and revised the manuscript. VKT and VD revised the manuscript. MM prepared the figures and assisted in drafting the manuscript. BK prepared the tables. AKT assisted in structuring and organising the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interests to declare.

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