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## POSTHARVEST PHYSIOLOGY, STORAGE STRATEGIES AND SHELF-LIFE OPTIMIZATION OF CUCURBITACEOUS VEGETABLES: A REVIEW

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### ABSTRACT

The cucurbitaceous vegetables (cucumber, melon, pumpkin, squash and gourds) are horticultural commodities globally, which play a significant role in food security, nutrition and as well as agricultural economies. But due to higher water content, thin epidermal composition and continued metabolic activity after harvest make them very perishable resulting in significant postharvest losses across the supply chain. This review is a critical synthesis of available information on the postharvest physiology, storage and shelf life of cucurbitaceous vegetables with special reference to the physiological and molecular aspects of the quality loss. Important postharvest processes such as respiration, ethylene production, transpiration, enzymatic activity, oxidative stress and chilling injury are discussed and the effects of these processes on texture, colour, nutritional value, and marketability are dealt with. The review also compares the traditional and innovative storage technologies such as the temperature and humidity control, the systems of the controlled and modified atmosphere, edible coatings and active packaging. The use of emerging physical and chemical intervention methodologies like ultraviolet irradiation, heat treatments, high voltage electrostatic fields, light emitting diode, electrolyzed water, ethylene inhibitors, calcium salts, melatonin, essential oils and biological control agent are reviewed with regard to their potential in delaying senescence, alleviating microbial degradation and stress induced tolerance. Novel developments in multi-omics technologies, non-destructive sensors and Internet of Things based monitoring techniques and sustainable packaging materials are also mentioned as disruptive technologies of precision postharvest management. This review offers a holistic approach to the development of crop specific, environmentally friendly and scalable postharvest solutions by integrating physiological, biochemical and technological approaches. The results highlight the need of systems level interventions to reduce losses and prolong shelf life in addition to global initiatives of sustainable agriculture and food security.

**Key words :** Cucurbitaceous vegetables, Postharvest physiology, Shelf-life optimization, Chilling injury, Ethylene regulation, Respiration and transpiration.

### Introduction

Cucurbitaceous vegetables are a broad range of

vegetable family which consists of the economically valuable crops such as cucumber (*Cucumis sativus* L.),

melon (*Cucumis melo* L.), pumpkin (*Cucurbita pepo*) and squash. Such crops are very important in world food security and human nutrition because they contain high water, dietary fibre, vitamins and bioactive compounds. India is the second largest producer of vegetables worldwide, highlighting the agricultural and economic importance of cucurbitaceous crops in both domestic and export markets (FAO, 2021; Ministry of Agriculture and Farmers Welfare [MoAFW], 2022). Cucurbitaceous vegetables are very perishable because of their nutritional and economic importance and are prone to significant losses after harvest. It is estimated that annual losses of fruits and vegetables in the postharvest phase would be between 28-55% and worse in the low-income and middle income countries because of poor handling practices and insufficient infrastructure to preserve them (Hodges *et al.*, 2011; Affognon *et al.*, 2015). The elevated perishability of cucurbits has been largely explained by the fact that it goes on with metabolic activities after harvesting, such as respiration, transpiration and the ripening process, which enhance the process of quality degradation and microbial spoilage (Wills *et al.*, 2007).

Physiological processes that occur after harvest are extremely complex and are controlled by a complex set of enzymes and metabolic functions linked to cell wall breakage, ethylene production and oxidative stress (Klee *et al.*, 2011). Of these, the important plant hormone ethylene is the most considerable in controlling fruit ripening and senescence through increasing the rate of softening, chlorophyll degradation and tissue aging. Cucumbers (*Cucumis sativus* L.) being among the largest cucurbitaceous vegetables are highly sensitive to conditions of the environment and their shelf life is highly dependent on the temperature, relative humidity and mechanical force during handling and transportation (Suslow *et al.*, 2009). Other physiological indices that have been reported to be useful are total soluble solids (TSS) and dry matter content (DMC) at harvest as predictors of postharvest behaviour and shelf-life potential of cucumbers. The need to minimize food losses, improve food security and maximize economic returns to producers and distributors can be achieved by maintaining the best postharvest quality and extending shelf life of food (FAO, 2011). In order to reduce the high level of postharvest losses, a lot of research has been conducted on the design and implementation of efficient storage and shelf-life extension measures among cucurbitaceous vegetables (Singh *et al.*, 2018). Traditional forms of storage have been found to have limitations despite their simplicity and low cost. The use of low-temperature storage is usually aimed at decelerating the respiration rate and inhibiting

the growth of microorganisms but cucumbers and other vegetables sensitive to chilling may develop physiological disorders including surface pitting, water-soaked lesions and discolouration as a result of low temperatures that are below their tolerance range. These constraints underscore the fact that more research is needed in terms of the study of postharvest physiology that can be able to design preservation methods in a way that is specific to the requirements. Innovative management methods have been developed and optimized due to the current developments in postharvest technology. The use of advanced physical techniques like controlled atmosphere (CA) storage and modified atmosphere packaging (MAP) controls the levels of gases around the produce and this helps to minimize respiration, ethylene activity and loss of moisture. The research done in cucumbers stored at cool temperatures in combination with the use of passive modified atmosphere bulk packaging shown that the quality of the product and the shelf-life were significantly improved (Mahajan *et al.*, 2014). Some of the newer physical processes such as heat treatment, ultrasound and ultraviolet (UV) radiation have shown encouraging findings in regards to microbial inactivation, senescence delay and resistance mechanisms induction of fresh produce. Among the non-chemical methods, the application of UV-C has been mentioned to increase resistance to diseases and preserve the quality of harvests in fruits and vegetables by promoting the absence of resistance to defence related biochemical processes.

Chemical preservation is also utilized and it involves, inorganic and organic compounds. Calcium salts mostly used to make fruits firmer by cross linking the pectin molecules in the cell walls (Chen *et al.*, 2024). It is mentioned that the use of calcium oxide nanoparticles in the biocompatible polymeric coating has an impact on improving the quality of cucumber fruit during postharvest storage (Cid-Loep *et al.*, 2021). Organic compounds, melatonin, 1-methylcyclopropene (1-MCP) and  $\epsilon$ -poly-L-lysine are used as antioxidant, anti-senescence as well as antimicrobial properties respectively. Exogenous ATP has also been mentioned as a resource that can be used to stimulate the physiological to guarantee quality in the postharvest fruits and vegetables (Shan *et al.*, 2023). The advanced technologies, such as the use of multi-omics approaches, can be combined to deliver the improved understanding of the molecular processes occurring during the postharvest physiology that can provide information regarding the processes of gene expression, protein activity and metabolic processes that determine the quality and nutritional characteristics (Habibi *et al.*, 2024). This is a crucial fact in the molecular level to make certain

interventions in order to extend the shelf life. It is because cell wall polysaccharides are formed in the process of shrivelling and it can be influenced by different factors like vibration and broken cold chains during transportation, the intricate physiological processes that influence the quality of postharvest (Zhang *et al.*, 2023). Overall, the problem of the physiology of postharvest, optimization of storage and shelf-life of cucurbitaceous vegetable should be investigated in details. Such review involves the expertise of molecular biology, biochemistry and engineering to aid overcome the problem of massive postharvest losses, a move that has contributed to the attainment of agricultural sustainability and food security among the global community (Zhang *et al.*, 2023; Habibi *et al.*, 2024).

### Postharvest Physiology of Cucurbitaceous vegetables

Physiology of postharvest of cucurbitaceous vegetables is a complicated interplay of natural biological processes that significantly influence its quality and marketability. They are respiration, ethylene synthesis, transpiration, sensitivity to enzyme activity and chilling injury and all of them are species specific (Umeohia *et al.*, 2024). These mechanisms require knowledge in the development of effective postharvest handling and storage methods to improve the shelf lifetime and reduce losses (Chen *et al.*, 2024).

#### Respiration

One of the major metabolisms that determine post harvest quality, physiological degradation and shelf life of cucurbitaceous vegetable is respiration. Most commonly non climacteric crops, such as cucumber (*Cucumis sativus*), zucchini (*Cucurbita pepo*), pumpkin, bitter melon (*Momordica charantia*) and bottle gourd (*Lagenaria siceraria*) do not exhibit a sharp ethylene related respiratory peak in their ripening (Valenzuela *et al.*, 2017). They are rather active in respiration and also impressively influenced by the environmental factors and temperature in particular. High respiration rate increases the rate of carbohydrate degradation, loss of firmness, loss of moisture and vulnerability to microorganisms, thus the control of respiration is central to postharvest management. The strongest impact on the respiration kinetics in cucurbits is produced by temperature. The value of  $Q_{10}$  is usually between 2.0 and 2.8 which means that the respiration increases 2-3 times with every increment of 10°C. As an example, the respiration rate of cucumber rises as a factor of around 7 mL CO<sub>2</sub> kg<sup>-1</sup> h<sup>-1</sup> at 5°C to over 32 mL CO<sub>2</sub> kg<sup>-1</sup> h<sup>-1</sup> at 20°C respectively (Madhura *et al.*, 2021). These exponential reactions are

the reason why quality is so readily degraded when stored in less than optimal conditions. Even though there is low temperature-induced respiration inhibition, chilling-receptive cucurbits such as zucchini could have stress induced ethylene production on rewarming, dependent on the degree of chilling injury (Megías *et al.*, 2016). A number of postharvest technologies are invented to control respiration. A modified atmosphere wrapping (MAP) slows down metabolic activity by keeping the O<sub>2</sub> (<5%) levels low and the CO<sub>2</sub> (>5-10%) levels high without causing anaerobiosis (Sun *et al.*, 2023). Investigations of fresh-cut cucumber reveal the significance of balancing respiration, gas permeability and microbial development in MAP systems. Edible coatings such as chitosan-based formulations also inhibit gas exchange and transpiration, which in effect slows down respiration and decay (Chen *et al.*, 2024).

Table 1 say about the key respiration characteristics and optimal storage parameters for several important cucurbitaceous vegetables, providing a practical reference for postharvest management. The variation in respiration underlies differences in storability of cucurbits with winter squash experiencing lower metabolic rates compared to the highly perishable cucumber and zucchini (Viaene *et al.*, 2017). New sensor-based and non-invasive technologies will provide promising possibilities of real-time monitoring of respiration to improve future postharvest management strategies (Keshri *et al.*, 2019; Pieczywek *et al.*, 2024).

#### Ethylene Production

The cucurbitaceous vegetables ethylene production poses a physiological contradiction in the postharvest management. Contrary to the climacteric fruits, like tomato and banana, which have a marked autocatalytic ethylene burst during the ripening process, cucurbitaceous crops (cucumber, zucchini and melon) are considered as non-climacteric or weakly climacteric because of their low endogenous ethylene production. Cucumber, as an example, mere not more than 0.01–0.1 µL C<sub>2</sub>H<sub>4</sub> kg<sup>-1</sup> h<sup>-1</sup> at 20°C, which is many orders of magnitude below the peak of >10 µL kg<sup>-1</sup> h<sup>-1</sup> in ripening recorded in tomato (Tiribolulu *et al.*, 2024). This low production is not withstanding the fact that cucurbits are very sensitive to exogenous ethylene, the management of which is essential in terms of improving the shelf-life. The perception of ethylene is therefore, more important in postharvest quality deterioration of cucurbits than internal synthesis. Exposure to the lowest level of ethylene (0.1 µL L<sup>-1</sup>) promotes the peel yellowing and incidence of decay in cucumber (Tiribolulu *et al.*, 2024). Likewise, in zucchini

**Table 1** : Variation in respiration rates.

| Crop                                           | Respiration Rate<br>(mL CO <sub>2</sub> kg <sup>-1</sup> h <sup>-1</sup><br>at 20°C) | Optimal Storage<br>Temp. (°C) | Approx. Shelf-<br>Life (days) | Reference                    |
|------------------------------------------------|--------------------------------------------------------------------------------------|-------------------------------|-------------------------------|------------------------------|
| Cucumber ( <i>Cucumis sativus</i> )            | 15–25                                                                                | 10–12                         | 10–14                         | Kaur <i>et al.</i> (2021)    |
| Zucchini ( <i>Cucurbita pepo</i> )             | 20–35                                                                                | 7–10                          | 7–10                          | Zhang <i>et al.</i> (2017)   |
| Bitter Gourd ( <i>Momordica charantia</i> )    | ~18                                                                                  | 12–15                         | 14–21                         | Madhura <i>et al.</i> (2021) |
| Bottle Gourd ( <i>Lagenaria siceraria</i> )    | ~10                                                                                  | 10–15                         | 21–28                         | Madhura <i>et al.</i> (2021) |
| Butternut Squash ( <i>Cucurbita moschata</i> ) | 2–5                                                                                  | 10–15                         | 90–180                        | Viaene <i>et al.</i> (2017)  |

**Table 2** : To better demonstrate the differences in ethylene physiology between cucurbits and other vegetable.

| Crop (cultivar)            | Ethylene<br>Production<br>( $\mu\text{L C}_2\text{H}_4/\text{kg}\cdot\text{h}$ ) | Ripening type   | Postharvest Ethylene response                                              | Reference                       |
|----------------------------|----------------------------------------------------------------------------------|-----------------|----------------------------------------------------------------------------|---------------------------------|
| Cucumber<br>(‘Beit Alpha’) | 0.02–0.05                                                                        | Non-climacteric | Yellowing, decay $\uparrow$ at $\geq 0.1 \mu\text{L/L}$                    | Tiribolulu <i>et al.</i> (2024) |
| Zucchini<br>(‘Nero’)       | 0.03–0.08                                                                        | Non-climacteric | Peduncle abscission $\uparrow$ , firmness<br>loss $\uparrow$               | Moya <i>et al.</i> (2020).      |
| Muskmelon<br>(‘Athena’)    | <0.01 (basal)                                                                    | Non-climacteric | Softening & aroma synthesis $\uparrow$<br>with $10 \mu\text{L/L}$ ethylene | Moya <i>et al.</i> (2020)       |
| Tomato<br>(‘Roma’)         | 5–15 (peak)                                                                      | Climacteric     | Used as positive control for<br>ethylene assays                            | Nguyen <i>et al.</i> (2024)     |

squash, ethylene induces peduncle abscission and fast softening, although endogenous production of ethylene is low (Moya *et al.*, 2020). This low biosynthesis and high sensitivity combination implicates the postharvest strategy not suppressing ethylene production, e.g. by ACC synthase inhibition, reducing the exposure of ethylene or the inhibition of its activity. The research findings in the recent past have brought forward the efficacy of ethylene action inhibitors in storage of cucurbit. Application of 1-methylcyclopropene (1-MCP), an antagonist of the ethylene receptor, on cucumber greatly slowed and postponed the yellowing process and ensured firmness of up to 14 days under cold conditions. Irreversible binding of 1-MCP to the ethylene receptors inhibits downstream signalling related to senescence which effectively intercepts the physiological reaction to ethylene as opposed to its own synthesis which is already low.

Table 2 highlights an important consideration in postharvest physiology the effect of ethylene on a produce item is not dependent on its production rate, but rather on the tissue’s sensitivity to the hormone. For figleaf gourd (*Cucurbita ficifolia*) studies have shown its non-climacteric status, with low and steady respiration and ethylene production rates throughout its life cycle, which further reinforces the overall trend in the family (Moya *et al.*, 2020). Therefore, the most effective storage

methods for cucurbits are those that utilize technologies that either remove the ethylene from the package headspace, such as potassium permanganate-based active packaging (Tiribolulu *et al.*, 2024), or those that utilize antagonists such as 1-MCP to inhibit its action at the receptor level.

### Transpiration and Water loss

Transpiration is associated with water loss, represent a major postharvest physiological challenge in cucurbitaceous vegetables, directly affecting visual quality, texture, marketability and shelf life. Crops such as cucumber (*Cucumis sativus*), zucchini (*Cucurbita pepo*), bitter gourd, bottle gourd and muskmelon (*Cucumis melo*) possess a high surface area to volume ratio, thin cuticle and high moisture content, making them highly prone to rapid dehydration once detached from the parent plant (Gidado *et al.*, 2024). Transpiration occurs due to the vapor pressure gradient between the moist internal tissues and the drier storage atmosphere, resulting in shrivelling, loss of turgor, surface dullness and increased susceptibility to mechanical injury and microbial decay, thereby accelerating senescence and reducing consumer acceptability (Zhang *et al.*, 2023).

The amount of water loss among the species and cultivars is variable and regulated by intrinsic and extrinsic factors. The intrinsic determinants are cuticular thickness

and composition, stomatal density (lowest in mature fruits) and cell wall integrity. As an example, muskmelon has a relatively high cuticular conductance ( $1.824 \times 10^{-7} \text{ m s}^{-1}$ ), which makes it dry out faster than other crops, including tomato (Olawaju *et al.*, 2023). Transpiration rates are very sensitive to extrinsic factors especially temperature and relative humidity. Research of European suggests that in cucumber temperature and humidity changes have an important negative impact on shelf life and weight loss and also one of the main predictors of quality reduction (Rodriguez *et al.*, 2023). Bruised cucumbers kept at a higher temperature (22°C) experience significantly higher water loss and inferior quality compared to bruised cucumbers kept at 5°C (Al-Hadrami *et al.*, 2023). New fast, inexpensive methods of transpiration measurements have been developed recently only to emphasize the necessity of this water loss monitoring in order to evaluate the impact of the preharvest and postharvest factors. A number of mitigation measures have worked. Food grade biopolymers and edible coatings are semi permeable barriers, which slow the diffusion of moisture but do not trigger an anaerobic respiration zucchini coated with aloe vera has been reported to extend quality in glutted zucchini (Al Lawati *et al.*, 2024). Photocatalytic surfaces which degrade ethylene when exposed to UV light lessen respiration and resultant water loss in cucumber.

Additionally, transgenic cucumber lines expressing poly- $\gamma$ -glutamic acid synthesis genes demonstrated reduced water loss and increased water retention (Li *et al.*, 2024). Modified atmosphere packaging (MAP) remains a cornerstone technology, as it lowers vapor pressure deficit by maintaining high relative humidity (>95%) and optimized gas composition, thereby effectively extending shelf life when properly designed (Rashvand *et al.*, 2023).

Table 3. supports the importance of a multi-faceted strategy that incorporates optimal environmental conditions (low temperature, high RH), physical barriers (edible coatings) and advanced packaging technology (MAP) in the effective management of transpiration and the extension of the marketable shelf life of highly perishable cucurbitaceous vegetables. Future studies must continue to develop sustainable, food-grade coatings and improve models of water loss.

### Enzymatic activity

Enzymatic activity is a dominating factor that defines postharvest quality, senescence and shelf life of cucurbitaceous vegetables like cucumber, melon, pumpkin and squash. The most important enzymes as listed in Tabel 4. includes PG, PME and PL, are cell wall-modifying enzymes that are collectively involved in the regulation of fruit softening. PME catalyses pectin de-esterification, allows breakage of the pectin through subsequent depolymerization of the pectin by PG and PL, leading to weakening of the middle lamella and loss of firmness during storage and ripening. Molecular and physiological research on melon and other fleshy fruits in the recent past has confirmed that overexpression and activity of these enzymes have close relationship with post-harvest softening, especially with higher storage temperatures (Shi *et al.*, 2023; Wang *et al.*, 2024). oxidative enzymes like polyphenol oxidase (PPO) and peroxidase (POD) play an important role in browning responses, membrane stability and defence through post-harvest in fresh-cut or mechanical damaged cucurbits. On the other hand, antioxidant enzymes like Superoxide dismutase (SOD), Catalase (CAT) and Ascorbate Peroxidase (APX) act as a protective system. They also scavenge the Reactive Oxygen Species formed under stress conditions like chilling or wounding. There are correlations between

**Table 3 :** Water loss in cucurbitaceous vegetables during storage.

| Crop                                    | Storage/treatment Condition            | Time Frame | Weight Loss (%)                | Contributing Factors / Reference                                                                     |
|-----------------------------------------|----------------------------------------|------------|--------------------------------|------------------------------------------------------------------------------------------------------|
| Cucumber ( <i>C. sativus</i> )          | 20°C, 65% RH (ambient)                 | 48 h       | 4.2–5.8                        | Thin cuticle, high epidermal permeability (Das <i>et al.</i> , 2022)                                 |
| Zucchini ( <i>C. pepo</i> )             | 10°C, 90% RH                           | 72 h       | 3.1–3.7                        | Microcracks, rapid cutin oxidation (Al Lawati <i>et al.</i> , 2024)                                  |
| Muskmelon ( <i>C. melo</i> )            | 25°C, 60% RH                           | 96 h       | 6.5–8.0                        | High residual stomatal density, low wax content (Olawaju <i>et al.</i> , 2023)                       |
| Bitter melon                            | 15°C, 85% RH + Chitosan coating (1.5%) | 12 days    | 2.4 (coated) vs. 7.1 (control) | Coating-induced barrier resistance to H <sub>2</sub> O vapor (Chen <i>et al.</i> , 2024)             |
| Butternut squash ( <i>C. moschata</i> ) | 13°C, 90–95% RH + MAP                  | 21 days    | 1.9 (MAP) vs. 5.3 (control)    | Reduced O <sub>2</sub> /CO <sub>2</sub> -modulated cuticle hydration (Rashvand <i>et al.</i> , 2023) |

**Table 4 :** Enzymes involved in postharvest quality changes.

| Enzyme                                                                 | Role (postharvest effect)                      | Example / observed effect in cucurbits                                                                        |
|------------------------------------------------------------------------|------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| Polygalacturonase (PG)                                                 | Pectin depolymerization → softening            | PG increases during melon ripening and correlates with firmness loss (Shi <i>et al.</i> , 2023)               |
| Pectin methylesterase (PME)                                            | Demethylates pectin → substrate for PG/PL      | PME activity rises early in storage; Ca <sup>2+</sup> treatments reduce softening (Wang <i>et al.</i> , 2024) |
| Pectate lyase (PL)                                                     | Cleaves de-esterified pectin → rapid softening | PL associated with late-stage softening in cucurbit fruits (Shi <i>et al.</i> , 2023)                         |
| Polyphenol oxidase (PPO)                                               | Oxidizes phenolics → browning                  | Elevated in damaged and fresh-cut melon tissues.                                                              |
| Peroxidase (POD)                                                       | ROS metabolism, tissue defence                 | POD activity linked to reduced decay under Ca/SA treatments (Wu <i>et al.</i> , 2024)                         |
| Lipoxygenase (LOX)                                                     | Lipid oxidation → volatiles/off-flavours       | Increased LOX associated with off-flavour development in stored melon (Wu <i>et al.</i> , 2024)               |
| Superoxide dismutase (SOD), Catalase (CAT), Ascorbate Peroxidase (APX) | Antioxidant defence → delayed senescence       | Higher activity improves storage tolerance in cucurbits (Wang <i>et al.</i> , 2024)                           |

increased antioxidant enzyme activity and reduced senescence and physiological disorders in storage of melons and cucumbers (Wu *et al.*, 2024). Another significant enzyme playing a role in the process is lipoxygenase (LOX) and this plays a role in the quality of the crop at the post-harvesting stage, owing to its involvement in the lipid peroxidation reaction and volatile production in the crop. While LOX produced volatiles play a significant role in the development of traditional flavour quality, overactivity can be disadvantageous at the post-harvesting storage level, leading to an unflavoured product and degradation of the membranes. These aforementioned enzymatic activities have shown a moderate effect from the controlling conditions at the post harvest level (calcium treatment, controlled atmosphere and use of elicitors like salicylic acid) to help preserve the quality, flavour and texture of cucurbitaceous vegetables during the period of storage (Wang *et al.*, 2024).

### Chilling injury

Chilling Injury (CI) is a physiological condition of relevance to postharvest quality and cost effective value of cucurbitaceous vegetables, which are recognized to have tropical and sub tropical origin and are very vulnerable to low non-freezing temperature. Although, the freezing injury takes place at temperatures between 0°C and 15°C (which is considerably high compared to the freezing point of these crops), but considerably lower than the optimum storing temperature of the crops, the lesion of the cell caused by chilling injury is also related to the membrane of the cells. When the cell is in a chilling stress, the membrane lipids are changed to a more solid

state of a gel due to increased saturation of the fatty acids (Tomita *et al.*, 2023). This causes the loss of the semi permeability of cell membranes and thus, the uncontrolled loss of electrolytes which has been identified as a conventional quantitative practical of chilling injury severity (Zhang *et al.*, 2023). The disturbance of the balance of electrolytes causes a cascade of pathologic consequences on the cell, lead to the development of additional doses of reactive oxygen species such as superoxide anion (O<sub>2</sub><sup>-</sup>) and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) (Lin *et al.*, 2022). The overproduction of ROS, when it overcomes the antioxidant defence ability of the fruit (which includes the enzymes of superoxide dismutase (SOD), catalase (CAT) and ascorbate peroxidase (APX)) causes oxidative stress. As a response of oxidative stress, lipid peroxidation occurs, which is a reaction between ROS and membrane bound or intracellular polyunsaturated fatty acids resulting in cell damage and the production of cytotoxic products like malondialdehyde (MDA), another significant biochemical indicator of CI (Lu *et al.*, 2023). Oxidative stress does not only affect the integrity of membranes but also affects the proteins, DNA and other cellular functions like energy production. CI has been associated with impaired primary metabolism in a study of Cucumber plants of the genus *Cucumis sativus* L. and a significant decrease in cellular energy levels, which were reflected in a reduction in intracellular ATP. CI has been linked to impaired energy production and redox homeostasis inability in Zucchini *Cucurbita pepo*, another species of the Cucurbit family (Yi *et al.*, 2024). The recent literature focused on the clarification of the molecular processes along with preventing actions of its

prevention. In order to give an example, exogenous administration of signalling molecules like nitric oxide (NO) and hydrogen sulphide (H<sub>2</sub>S) showed a definite inhibitory effect on CI in cucumber through not only enhancing the activity of antioxidant enzymes but also the stability of energy metabolism (Ali *et al.*, 2023). In addition, the phytohormonal mitigants like abscisic acid (ABA) and melatonin were also effective in alleviating CI in zucchini through the regulation of the levels of specialty metabolites, non-enzymatic antioxidants (phenolic compounds and ascorbic acid) and through cell wall integrity (Ali *et al.*, 2023). Near-freezing temperature storage, which has somewhat contradictory negative effects in the regulation of CI in some fruits like guava and apricot, is one such physical strategy that has shown a significantly good outcome in controlling the CI symptoms by suppressing the comparably constant cellular condition and promoting the antioxidant enzyme activities (Li *et al.*, 2022 and Xiao *et al.*, 2022).

Table 5 points to the species specificity of CI and underscores the need for crop specific postharvest research and handling. The interface between physiological knowledge and technologies such as omics technologies (transcriptomics and metabolomics) has helped to create an integrated view of processes that regulate CI, which will lead to more precise and effective approaches for optimizing the postharvest life of such economically important vegetables (Habibi *et al.*, 2024 and Li *et al.*, 2024).

### Postharvest quality and Spoilage

The complicated interaction of physiological, biochemical and microbiological events that directly affect consumer acceptability, market value and food security controls postharvest quality and spoilage of fresh produce.

Postharvest quality management depends on preservation of the main attributes, including firmness, colour, flavour, nutritional content and at the same time avoiding the spoilage processes, microbial degradation, physiological diseases and environmental stresses (Chen *et al.*, 2021). All this contributes to the shelf life and safety of the fruits and vegetables between their harvesting and delivery to the consumers. Firmness is an important physical characteristic that demonstrates the textural integrity and is mostly predetermined by the structural stability of the cell walls and the middle lamellae. In postharvest storage, pectin, cellulose and hemicellulose are broken down into softened by enzymes of polygalacturonase, pectin methyl esterase and cellulase activities (Chen *et al.*, 2021). Cuticular wax being a primary contributor in the firmness of the fruit by reducing transpiration loss of the wax itself enhances the rate of decay leading to shrivelling of blueberries (Chu *et al.*, 2018). Colour is one of the main visual references of freshness and ripeness. It is also affected by pigments like chlorophylls, carotenoids and anthocyanins the synthesis and breakdown of which are highly controlled during senescence. High hydrostatic pressure of mild intensity (20 - 80 MPa) in mangoes has been demonstrated to promote carotenoid biosynthesis and subsequently the carotenoids have been associated with the development of colour and the retention of bioactive compounds into the fruit (Hu *et al.*, 2021). Sensory attributes such as flavour and aroma are made by volatile organic compounds (VOCs), sugars, acids and by the addition of esters. The accumulation of ethanol and ethyl acetate through anaerobic respiration yields undesirable Odor of alcohol and pungency (Zhao *et al.*, 2024). An electronic sensing of VOC profiles is a non-destructive technique of real-time quality control during storage (Tiwari *et al.*, 2020). The nutritional value such

**Table 5 :** Chilling Injury Symptoms and Biochemical markers in Sensitive Crops.

| Crop                                                 | Critical Temp. (°C) | Primary Symptoms                                    | Onset Time (Days) | Biochemical Markers                                              | Reference                  |
|------------------------------------------------------|---------------------|-----------------------------------------------------|-------------------|------------------------------------------------------------------|----------------------------|
| <b>Cucumber</b><br>( <i>Cucumis sativus</i> )        | <10                 | Pitting, water-soaking, decay                       | 5–7               | ↑ MDA, ↑ H <sub>2</sub> O <sub>2</sub> , ↓ SOD & CAT activity 14 | Min <i>et al.</i> (2025)   |
| <b>Zucchini</b><br>( <i>Cucurbita pepo</i> )         | <8                  | Yellowing, softening, surface lesions               | 3–5               | ↑ LOX, ↑ electrolyte leakage, ↓ ATPase 1310                      | Tossi <i>et al.</i> (2024) |
| <b>Muskmelon</b><br>( <i>Cucumis melo</i> )          | <7                  | Rind discoloration, loss of aroma, flesh softening  | 6–10              | ↓ Ascorbate peroxidase, ↑ ethylene burst 14                      | Ning <i>et al.</i> (2022)  |
| <b>Sweet Bell peper</b><br>( <i>Capsicum annum</i> ) | <7.5                | Surface pitting, shrivelling, uneven ripening       | 7–10              | ↑ NADPH oxidase activity, altered glycine betaine 1516           | Xu <i>et al.</i> (2023)    |
| <b>Avocado</b> ( <i>Persea americana</i> )           | <6                  | Skin pitting, mesocarp darkening, abnormal ripening | 10–14             | Disrupted ROS and cell wall metabolism 1718                      | Guo <i>et al.</i> (2023)   |

as vitamin C, total phenolics, flavonoid and carotenoids is dynamic after harvest. High hydrostatic pressure intervention in mango preserves and enhances the antioxidant substances like vitamin C and total phenolics as compared to the control conditions (Hu *et al.*, 2021). Natural organic acids which include citric and malic acid have shown efficacy in preserving nutritional quality by regulating enzymatic browning and oxidative processes (Zhang *et al.*, 2023).

### **Microbial decay**

Microbiological spoilage is one of the most common instances of postharvest spoilage and fungi are especially destructive. *Penicillium expansum*, the cause of blue Mold rot, infects a variety of fruits (apples, pears, or citrus) causing mycotoxin synthesis (patulin), which is deadly to humans (Wills *et al.*, 2016; Ezzouggari *et al.*, 2024). *Botrytis cinerea* is a fungal disease that causes Gray Mold in strawberries and other berries, mostly spreads quickly in the course of storage and transportation when there is high moisture content (Wills *et al.*, 2016). Biological control methods that use antagonistic microbes use the competition of nutrients and space, antibiosis, parasitism and host resistance induction as methods of reducing these pathogens (Amalizadeh *et al.*, 2011). Recent developments focus on microbiome-based strategies in which the advantageous microbial communities are designed to defeat or dishearten destructive species (Kuruppu *et al.*, 2024).

### **Physiological disorders**

Physiological disorders in cucurbitaceous vegetables are non-pathogenic and occur as a result of environmental stresses, biochemical alterations and improper management after harvest, thereby creating substantial deterioration and loss of storage time (Kader *et al.*, 2002; Wills *et al.*, 2016). Chilling injury is a very dominant type of physiological disorder among cucumber, zucchini, gourd and melon products after storage below critical limits of chilling temperatures as a result of disruptions in product membranes, pitting on surfaces, water-soaked lesions, translucence of flesh and greater levels of spoilage (Wang *et al.*, 2019). Improper management of temperature and relative humidity during handling also contributes to product surface pitting, excessive loss of moisture, shrivelling and loss of product firmness, thereby contributing to greater loss of acceptability (Paull *et al.*, 2008; Gross *et al.*, 2016). While many cucurbits have low endogenous ethylene production, exposure of cucurbits to exogenous ethylene can stimulate chlorophyll loss, softening and several senescence-related biochemical reactions (Lee *et al.*, 2011). Cell wall degradation enzyme activity and calcium

homeostasis have also been implicated in the internal breakdown and flesh softening syndromes of melons and pumpkin after harvest (Lester *et al.*, 2007; Vicente *et al.*, 2009). Heat stresses and sunscald injuries of cucurbit fruits also occur before harvest and can cause various types of skin and flesh deterioration when they are stored (Paull *et al.*, 2011).

### **Storage strategies**

#### **Temperature and Humidity management**

Cucurbitaceous vegetables- cucumbers, zucchini and melons are perishable due to the presence of a large amount of water, metabolic activity and vulnerability to chilling injury and microbial spoilage, so require complex postharvest management. Good storage methods involve combination of temperature and humidity, modified or controlled atmosphere, edible covering and dynamic packaging technologies to sustain quality, lengthen the shelf life and spoilage. One of the methods on which the concept of slowing respiration rates and microbial growth in fresh produce is based on refrigerated storage. In the case of cucumbers, packaging at 10-15°C has been determined to decrease the extent of weight loss considerably relative to unpackaged controls that is, packaged cucumbers weight loss was restricted to 10.09% of initial weight losses after 18 days at 15°C whereas the weight loss of the unpackaged controls reaches up to 60.72% of initial weight losses (Singh *et al.*, 2024). Cucurbits are also very susceptible to chilling injury because of being kept at temperatures below their optimal levels of chilling injury, which is usually about 10°C. Physiological may be caused by exposure to temperatures close to 5°C. It is thus important that exact refrigeration management should be applied, balancing microbial inhibition with chilling damage prevention. The humidity is complementary in reducing the water loss, as well as turgor. During cold storage, relative humidity (RH) of 90-95% is advised to avoid desiccation as well as to avoid excessive condensation which may encourage fungal development. A high RH prevents loss of crispness and visual quality, especially when low amounts of processing are applied to cucumbers and cut surfaces are exposed to transpiration.

#### **Controlled Atmosphere (CA) and Modified Atmosphere Packaging (MAP)**

Controlled Atmosphere (CA) and Modified Atmosphere Packaging (MAP) are two of the best postharvest technologies that can be used to extend the shelf life and preserve the quality of highly perishable cucurbitaceous vegetables which include cucumber, zucchini, bottle gourd and other similar species. Both CA

and MAP act by changing the gaseous environment around the produce to delay metabolic activities and senescence in different ways. Controlled Atmosphere storage is a bulk storage method in which the gas mixture of the entire room of storage is accurately and dynamically controlled. The common CA conditions are low oxygen ( $O_2$ ) usually 2-5%, high levels of carbon dioxide ( $CO_2$ ) 3-10% and retention of low temperature and high relative humidity. This atmosphere has a direct inhibitory effect on respiration, ethylene synthesis and the action of microorganisms of rot. According to a study on cabbage, a non-cucurbit, but a model of relevance to leafy vegetables, CA (1.5 kPa  $CO_2$  and 6 kPa  $O_2$ ) was found to be as effective in preserving quality as traditional cold storage at 5°C, indicating that a large amount of energy can be saved in the cold chain (Gage *et al.*, 2024). An example such as studies of the so called 'Seval F<sub>1</sub>' tomatoes which is a climacteric fruit normally the reference to the study revealed that CA storage (5%  $O_2$  + 5%  $CO_2$ ) greatly maintained the firmness and commercial ability of the fruits when compared to the usual atmospheric storage (Dilmaçunal *et al.*, 2022).

Comparatively, Modified Atmosphere Packaging is a technology that is more commercially accessible and consumer oriented, which forms a custom atmosphere inside a single package or container. The altered atmosphere is obtained actively via a combination of natural respiration of the produce and the selective gas permeability of the packaging film, or watertight by flushing the package with a selective gas mix and then closing the package. This is aimed at achieving an Equilibrium Modified Atmosphere (EMAP) which maximizes preservation. MAP has been a very effective technique in the case of cucumbers, which is a significant area of research. A study established that cucumbers kept in LDPE packages at a given oxygen transmission rate (OTR) in 15°C of the package showed that there was a drastic reduction on weight loss (10.09%) than in the unpackaged ones (60.72%) after 18 days and they were also found to maintain a good firmness and ascorbic acid level (Singh *et al.*, 2023). In another study involving fresh-cut cucumbers, it was found that fresh-cut cucumber with optimum MAP did not only increase the shelf life but was also effective in suppressing the growth of destructive *Escherichia coli* O157:H7 by down-regulating the important genes involved in bacterial movement and adhesion (Sun *et al.*, 2022). The efficiency of MAP strongly relies on the properties of the film a study of the various thicknesses of LDPE film discovered that the 37.5-micron thick film gave the most desirable weight loss reduction and retained sensorial properties in the

whole cucumbers. The main problem experienced by CA and MAP in using on the cucurbits is that they are sensitive to chilling injury (CI), which happens when the temperature is usually below 10-12°C. CI occurs in the form of pitting, surface browning and faster degradation. Hence, effective protocols tend to incorporate atmospheric control along with the measures to counteract CI. Indicatively, the cucumbers pre stored at cold temperatures of 10°C 24 hours before storage were demonstrated to have increased their chilling tolerance in subsequent cold storage due to the activation of their antioxidant defence mechanisms (Wang *et al.*, 2017). On the same note, in the case of zucchini, CI was mitigated under high relative humidity (98%) coupled with low temperature (4°C), which favoured the accumulation of protective proteins such as proline and abscisic acid (ABA) (Zuo *et al.*, 2021). Melatonin application exogenously was also reported to alleviate CI in zucchini during cold storage by improving antioxidant system and cell wall stability. The findings indicate that CA and MAP are not often used independently, but are best applied to an integrated approach of postharvest management.

### Edible coatings and Films

Edible coating acts as a physical barrier, which regulates the loss of moisture and gases. Chitosan, pectin, or cellulose based coating has been sprayed on cucumbers and other cucurbits to increase mechanical strength and slow softening. Chitosan limonene coatings with MAP preserved the firmness of cucumber and decreased the microbial load better than either of the treatments (Maleki *et al.*, 2018). Nanofiber composites based on pectin-cellulose can also be promising in creating uniform biodegradable surface films that can be used to improve surface protection without losing consumer acceptability (Panahirad *et al.*, 2021). These advantages are enhanced by active packaging, which includes the use of functional agents like ethylene scavengers or antimicrobials. Packaging, which has an ethylene scavenger, is found to extend the shelf life of cucumber and other cucurbits by alleviating the negative effects of ripening which are caused by adverse temperatures, particularly at temperatures less than ideal (Tiribolulu *et al.*, 2024). Such active systems are found to be much better than the conventional MAP in reducing yellowing and textural breakdown at 4°C. Together, all these combined strategies of refrigeration, humidity regulation, MAP&CA, edible coating and active ingredients constitute a multi-barrier measure, which would be fundamental in optimizing the postharvest quality of cucurbitaceous vegetables throughout the supply chain.

**Table 6 :** Application of CA and MAP to cucurbitaceous and other relevant horticultural crops.

| Crop                      | Technology     | Key conditions                                 | Storage temp.            | Primary Benefits                                                                 | Citation                        |
|---------------------------|----------------|------------------------------------------------|--------------------------|----------------------------------------------------------------------------------|---------------------------------|
| Cucumber                  | MAP            | LDPE, OTR of 2500 & 6000 cc/kg/24h             | 10°C & 15°C              | Reduced weight loss (from 60.72% to 10.09%), retained firmness and ascorbic acid | Singh <i>et al.</i> (2023)      |
| Cucumber                  | MAP            | 37.5-micron LDPE film                          | Ambient (22-26°C) & 10°C | Minimized physiological weight loss and colour change                            | Kargwal <i>et al.</i> (2021)    |
| Fresh-cut Cucumber        | MAP            | Optimized gas mixture                          | 4°C                      | Inhibited <i>E. coli</i> O157:H7 growth, maintained sensory quality              | Sun <i>et al.</i> (2022)        |
| Cabbage                   | CA             | 1.5 kPa CO <sub>2</sub> , 6 kPa O <sub>2</sub> | 5°C & 10°C               | Maintained quality at higher temperature, reducing energy demand                 | Gage <i>et al.</i> (2024)       |
| Tomato                    | CA             | 5% O <sub>2</sub> , 5% CO <sub>2</sub>         | 12±1°C                   | Improved marketability and firmness retention                                    | Dilmaçınal <i>et al.</i> (2022) |
| Chinese flowering Cabbage | MAP            | Passive MAP                                    | 20±1°C                   | Suppressed chloroplast dismantling, delayed leaf senescence                      | Mou <i>et al.</i> (2023)        |
| Zucchini                  | High RH + Cold | 98% RH                                         | 4°C                      | Alleviated chilling injury, maintained firmness                                  | Zuo <i>et al.</i> (2021)        |

### Shelf-life Optimization

To enhance the shelf-life of cucurbitaceous vegetables, it is important that the combination of pre-harvest agronomic practices and the application of subsequent, sophisticated, postharvest physical treatments are holistically implemented to preserve sensory, nutritional and microbial quality. Cucurbitaceous crops, such as cucumber, pumpkin, squash and melon are very perishable since they have a high water content, active rates of respiration and are susceptible to microbial decomposition and physiological disorders that lead to yellowing, softness and development of off-Odor (Jin *et al.*, 2022). Among these physiological disorders, chilling injury previously described in Section represents one of the most critical limitations to shelf life extension in cucurbitaceous vegetables stored under low temperature conditions. The ability to extend their marketability will depend on synergistic interventions that will reduce these degradation pathways using scientifically established means. The pre harvest conditions form the basis of pre harvest performance. The choice of cultivar has an immediate effect on natural shelf life, where some genotypes are experimentally observed to have increased cuticle thickness, cell wall integrity and antioxidant activity hence senescence and pathogen invasion are delayed (Yang *et al.*, 2025). Several agronomic measures, including optimized irrigation, nitrogen management system and supplemental lighting during cultivation have a substantial

influence on tissue composition and stress resilience. As an example, deficit irrigation in a controlled manner may enhance a build up in osmolytes, which maintains the turgor of a storage period, excessive nitrogen fertilization can stimulate high metabolic rates after harvesting, which accelerates the process of deterioration (Zdulskiet *et al.*, 2024). No phytochemical patterns or structural stability were also influenced by the environmental factors such as temperature and lighting and the substrate composition have also been tested, with the supplementary assimilation lighting of hydroponics providing greater post storage firmness and chlorophyll retention of cucumbers (Liu *et al.*, 2023).

### Physical treatments

#### Ultra violet radiation

The use of ultra-violet (UV) radiation has also become a viable non thermal physical method of enhancing the shelf life of cucurbitaceous vegetables by its dual effects of surface decontamination and physiological control mechanism. Specifically, UV-C radiation (200–280 nm) is an efficient residue free method that reduces the population of microorganisms and triggers host defence in fresh produce (Zhang *et al.*, 2019). The germicidal effect of it is mostly explained by its UV photon absorption capability on microbial nucleic acids, which lead to the formation of pyrimidine dimers, thus blocking DNA replication and transcription and inhibiting the spoilage microorganisms, including *Penicillium expansum*

(Song *et al.*, 2020). As an example, polyethylene-wrapped English cucumber showed a 2.5 log CFU g<sup>-1</sup> reduction and no degradation of visual and textural quality during 28 days at 5 °C with post-packaging UV-C treatment (560 mJ cm<sup>-2</sup>), which means that it is compatible with traditional packaging systems (Abdussamad *et al.*, 2016). In addition to destroying microbes, UV radiation alters postharvest physiology by causing slight oxidative stress that leads to antioxidant defence activation and phenolic metabolism through reactive oxygen species signalling (Naradisorn *et al.*, 2021). Despite the fact that the investigation of non-cucurbit crops, including broccoli, strawberry, was widely investigated, the findings are applicable because of the conserved nature of the UV-responsive pathways in angiosperms (Khalili *et al.*, 2016; Xu *et al.*, 2019; Zhu *et al.*, 2023). The use of UV-B supplementation in cucurbits has been demonstrated to increase the amount of cuticle and wax that is deposited on stems to minimize postharvest water loss. Although, UV radiation cannot be scaled and evenly delivered as a dose, the radiation still has a potential to be a promising, sustainable alternative to chemicals based shelf life extension in cucurbitaceous vegetables (Lysova *et al.*, 2024).

### Heat treatments

The heat treatment approach has proved to be an effective non-chemical physical postharvest technique in promoting the shelf life and quality maintenance of cucurbitaceous fruits, thereby suppressing the growth of microbial organisms, diseases and senescence (Paull *et al.*, 2008). The application of mild heat treatment, whereby cucurbit fruits undergo hot water, hot air, or vapor heat treatment, has shown promising effects in promoting the synthesis of heat shock proteins, protecting the cells, suppressing the occurrence of chilling injuries and improving the low-temperature storage qualities in cucumbers, squash and melon fruits. The heat treatment approach has effectively suppressed the ethylene production in cucurbit fruits, thereby suppressing the chloroplast sclerids, chlorophyll and ripening processes (McDonald *et al.*, 2013). Besides, thermal treatments decrease the surface microbial load and delay the enzymatic activity responsible for cell wall breakdown, which is linked to the better retention of firmness and a lower incidence of decays. Heat injury, surface scalding, or internal tissue damage may appear if temperature or duration is excessive (Paull *et al.*, 2008; Gross *et al.*, 2016).

### High-voltage Electrostatic Field (HVEF)

High voltage electrostatic field (HVEF) treatment is

an alternative technology that has been identified as promising in preserving cucurbitaceous vegetables, without undergoing thermal treatment. At 4 kV/cm, HVEF showed a profound effect on decreasing weight loss, rot incidence and pulp softening in cucumbers through controlling ion distribution across cell membranes thus stabilizing the structure of the cell and reducing electrolyte leakage (Łażny *et al.*, 2023). Research has indicated that HVEF (100 kV/m) is effective in short-term relative conductivity control of cucumber peel, which is an indication of membrane integrity, without affecting respiratory activity, which suggests selective inhibition of senescence mechanisms (Li *et al.*, 2023). When HVEF is used in conjunction with modified atmosphere packaging (MAP), gas equilibrium stability is improved, as is the inhibition of ethylene biosynthesis which increases the shelf life past 25 days- a necessary improvement of long-distance transport and naval supply chains (Zhang *et al.*, 2021 and Thilini *et al.*, 2022).

### Light-emitting Diode (LED) irradiation

Light-emitting diodes (LED) light has been used to exploit the wavelengths in the regulation of postharvest metabolic functions. The use of red and violet LEDs at 15 μmol/(m<sup>2</sup>·s) has been demonstrated to prevent the movement of water, the loss of soluble solids and the loss of chlorophyll and ascorbic acid in fresh-cut pak choi, which suggests its possible application to cucurbits (Zhang *et al.*, 2022). UVA-LED irradiation at 8 J/cm<sup>2</sup> not only prolonged the shelf life of minimally processed pak choi by two days but also augmented the quantity of phenolic acids and flavonoids and added to antioxidant properties (Zhou *et al.*, 2020). The process entails stimulating of the secondary metabolite biosynthesis and inhibition of polyphenol oxidase (PPO) activity. Although direct postharvest LED studies in cucurbitaceous vegetables remain limited, the involvement of conserved photoreceptor mediated signalling pathways, particularly phytochromes and cryptochromes, supports the translational relevance of these findings to cucurbit system which inhibits the enzymatic browning process. Red white LED and MAP lighting produce a two-layer protective layer against the acceleration of respiration and the growth of microbes to preserve the visual and texture qualities (Fan *et al.*, 2025).

### Electrolyzed Water (EW)

Electrolyzed water (EW), especially Acidic electrolyzed water (AEW) can be used as a useful surface decontaminant. It has been demonstrated that AEW treatment decreases the total bacterial, yeast and Mold counts on cucumber surfaces by up to 2.08 log CFU/g,

which is a significant reduction of spoilage without any chemical residues (Dan *et al.*, 2005). In combination with MAP, AEW increases the antioxidant enzyme activities, decreases the levels of malondialdehyde (MDA) and keeps the cell membrane permeable, thereby retaining freshness in cold storage). In the same way, slightly acidic electrolyzed water (SAEW) with ultrasound and UV-C LED has shown synergistic effectiveness when used with fresh-cut vegetables, highlighting its versatile antimicrobial efficacy (Ya *et al.*, 2023).

The combination of multiple technologies, including HVEF + LED + MAP or EW + ultrasonication + MAP, is a multi-hurdle strategy targeting various mechanisms of deterioration at once. Physics-based simulation-based digital twin modelling can be used to predictively optimize such combinations, measuring the effects of temperature, humidity and treatment parameters on the remaining shelf life (Koukounaras *et al.*, 2020). Such strategy at the systems level not only increases storability but also fits sustainable food supply chains by meeting the demand of consumers to eat the foods with minimum processing and no additives.

## Chemical treatments

### 1-Methylcyclopropene (1-MCP)

1-Methylcyclopropene (1-MCP) is a proven ethylene action inhibitor which has now become a standard in postharvest preservation technology because of its efficacy in slowing down ripening and senescence in climacteric fruit. The competitive ability to bind with ethylene receptors also causes 1-MCP to inhibit ethylene signalling, subsequently suppressing the autocatalytic production of ethylene that initiates fruit softening, colour changes and aroma formation (Jiang *et al.*, 2024). It has been shown in a variety of fruit species such as nectarines, apples, pears and mangoes. Even if cucurbitaceous vegetables belong to the category of non-climacteric vegetables overall, it is a fact that the physiology of post-harvest vegetables is highly sensitive to ethylene, especially regarding peel yellowing, softening and senescence-related disorders. Where 1-MCP treatment greatly prolonged shelf life by preserving firmness, chlorophyll degradation, titratable acidity and soluble solids (Jiang *et al.*, 2024; Liu *et al.*, 2005). As an example, in pears, Bartlett, a gaseous application of 1-MCP at harvest inhibited early ripening during cold storage and enhanced post-storage quality, however, the effects were variable with the maturity of the fruit and cold storage conditions (Escribano *et al.*, 2017; Villalobos *et al.*, 2011).

### Calcium salts

The importance of calcium salts in cell wall integrity

is to cross-link pectin molecules in the middle lamella and increase the rigor of the tissues and decrease their vulnerability to degradation by enzymes during storage (Frempong *et al.*, 2022). Applications of calcium chloride (CaCl<sub>2</sub>) pre-harvest (the foliar spray) or postharvest (dip) have been shown to have synergistic action with 1-MCP, especially in grapes and citrus, where they both reduced rachis browning, decay incidence and weight loss (Shi *et al.*, 2023; Frempong *et al.*, 2022). Stabilization of membrane permeability and inhibition of polygalacturonase activity is also another factor that helps in delayed deterioration in the texture.

### Essential oil

Essential Oils, which contain a large quantity of terpene (oxidizing) and phenolic (antioxidating) compounds, possess antimicrobial and antioxidant properties, both important in the control of postharvest pathogens and oxidative stress (Moradinezhad *et al.*, 2023). They are volatile and can be delivered in vapor phase and in this way, they can be used to disinfect the surface without direct contact, which is beneficial in enclosed storage systems. Nano emulsification increases the stability and dispersion of Essential Oil that increases their effectiveness in inhibiting spoilage organisms in fruits, including *Penicillium* spp. (Pinelli *et al.*, 2021). Mechanistically, EOs interfere with fungal membrane biogenesis by disrupting ergosterol biosynthesis and membrane permeability contributing to cellular leakage and inhibition of mycelial growth (Moradinezhad *et al.*, 2023).

### Melatonin

The pleiotropic molecule Melatonin is a potent postharvest anti-senescence and antioxidant agent. It changes the relative oxygen demand (ROS) scavenging pathways by enhancing the expression of antioxidant enzyme (including superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD)) and reduces oxidative injury in senescence (Yuan *et al.*, 2023). Melatonin alone and with 1-MCP was found to preserve ascorbic acid content, retain peel colour and decrease the formation of malondialdehyde in mangoes and therefore showed increased stability of the membrane (Yuan *et al.*, 2023). The power of control over the sugar processing and ethylene biosynthesis pathways makes melatonin a prospective natural substitute of synthetic preservatives.

### Biocontrol agents

Biological agents like *Pichia membranifaciens*, *Aureobasidium pullulans* and *Bacillus subtilis* provide ecofriendly solutions to control diseases in the form of competition, parasitism and host defence stimulation.

These microbes colonize wounds sites and synthesize antifungal metabolites that prevent the major postharvest pathogens such as *Botrytis cinerea* and *Penicillium expansum*. It is worth mentioning that the photodynamic technology that uses curcumin will form singlet oxygen when exposed to light and cause lethal oxidative stress on fungal cells and provides strong inhibitory actions against *Penicillium expansum* on apples (Godana *et al.*, 2023). This method integrates natural photosensitizers with physical activation which is in line with the consumer demand of preservation that leaves residues.

### Advanced Packaging systems

Smart active packaging systems combine both responsive materials that deliver preservatives, including 1-MCP, EOs, or Antioxidant to the environment in response to environmental conditions such as humidity, pH, or microbial activity (Cui *et al.*, 2024). Nanofibers electro spun to entrap bioactive compounds offer high surface area and kinetics-controlled release to ensure sustained protection throughout the supply chain. Ethylene scavenging multifunctional protection can be designed with titanium dioxide or antimicrobial delivery through silver nanoparticles.

### Emerging trends and technologies

Introduction of the new technologies into the process of postharvest management is creating a revolution in preservation, monitoring and distribution of fruits and vegetables throughout farm to consumer. This change is by a synergy of multi-omics sciences, non-destructive sensing, real-time monitoring systems, genetic engineering and sustainable packaging innovations all of which are combined towards reduction of food loss, improving quality and ensuring environmental sustainability.

### Multi-Omics Technologies: Decoding Postharvest physiology

The multi-omics technologies (such as genomics, transcriptomics, proteomics and metabolomics) are providing unprecedented understanding of the molecular pathway that regulates the postharvest physiology. This type of combined research allows researchers to deisolate such biological processes as ripening, senescence, chilling injury and pathogen resistance at different regulatory levels (Habibi *et al.*, 2024). As an example, it has been demonstrated through transcriptomic profiling that important genes are expressed in the ethylene biosynthetic pathway in ethylene signal transduction during climacteric fruit ripening and proteomic studies have identified stress-responsive proteins that prevail under cold storage conditions (Xie *et al.*, 2025). Metabolomics also supplements such data

by measuring dynamic variations in primary and secondary metabolites, such as sugars, organic acids, antioxidants and volatile compounds, which affect flavour, texture and nutrition value (Younas *et al.*, 2025). In kiwifruit, integrative omics have also clarified cultivar-specific reactions to storage conditions and thus has permitted accuracy interventions based on genetic background (Tilahun *et al.*, 2025). The strength of this practice is that it goes beyond observations to predictive processes of postharvest behaviours, which enables the creation of a specific treatment that can be directed by gene editing or metabolic modulators.

### Non-destructive Optical techniques

**Early Quality Deterioration Detection.** The non-destructive optical techniques are becoming very important in the real time and label free evaluation of quality of produce without affecting the integrity of the product. Early detection of the physiological disorders is possible through thermal imaging, hyper spectrophotometry, fluorescence spectroscopy and laser scattering. Thermal imaging with machine learning algorithms in eggplant, a vegetable with great susceptibility to chilling injury (CI), has proven to be highly accurate in detecting the onset of CI within 48 hours following the exposure to sub optimal temperatures (Tsouvaltzis *et al.*, 2020). These tools enable rapid sorting and elimination of damaged fruit in supply chains by identifying small amounts of changes in surface temperature distribution that occur during membrane damage and oxidative stress. Hyperspectral imaging, which works in both visible and near-infrared wavelengths, has the capacity to measure firmness, soluble solids content, pH and internal browning in apples and pears simultaneously, which are important parameters influenced by superficial scald and other chilling-related disorders (Rodrigues *et al.*, 2024). Combined with chemometric model these streams of data give powerful predictive ability of shelf-life and time of optimal consumption. These technologies not only improve on quality control but also facilitate traceability and automation of the modern packinghouses.

### Biosensor and IoT

**Dynamic Tracking of storage facilities.** The Internet of Things (IoT) system combined with the biosensing systems will allow real-time monitoring of the most important storage parameters such as temperature, relative humidity, ethylene concentration, O<sub>2</sub>, CO<sub>2</sub> and microbial load remotely. Small sensors installed in containers or retail shelves send information wirelessly to cloud-based analytics services to enable stakeholders to take preventative action when deviations are identified

(Lamsal *et al.*, 2024). In Nepal hilly areas, citrus farming the use of IoT grafting and storage systems has effectively increased the survival of saplings and the fruit marketability due to preservation of optimum micro climates (Lamsal *et al.*, 2024). Electrochemical biosensors, which use DNA nanomachines or employ enzyme conjugates, provide ultrasensitive sensors of bioindicators of spoilage biomarkers, including biogenic amines, ATP degradation products, or volatile organic compounds (MVOCs) produced by microbes (Wang *et al.*, 2020). They can be embedded in smart labels or smart packaging systems which show the status of freshness visually. Moreover, sensor-fed predictive microbiology models can enable dynamic shelf-life prediction to eliminate over-conservative expiration dates and to minimize unwarranted waste.

### Sustainable and Eco-friendly solutions

Sustainable packaging solutions is increasingly becoming popular as the world regulators work harder to restrict and the consumers are increasingly moving towards the use of products that are environmentally conscious. Plastic In modified atmosphere packaging (MAP) systems are now being supplied with biodegradable materials based on bagasse, chitosan, alginate and polylactic acid (PLA) (Mahmoud *et al.*, 2025). As an example, films made with chitosan contain an inherent antimicrobial effect and lowers the respiration rate of guava kept at low temperatures, maintaining a firmness and ascorbic acid levels further (Mahmoud *et al.*, 2025). Natural polymers can form edible coatings which can be enriched with antioxidants, essential oils or nanoparticles to provide other protective properties. These coatings serve as semi-permeable barriers which control gas exchange and loss of moisture and place active compounds directly on the fruit surface. In addition, they are in line with the principles of a circular economy as they will remove plastic waste. Life cycle assessments are shown to demonstrate that a biobased change in packaging will reduce carbon footprint and energy consumption across the supply chain (Rizzo *et al.*, 2025). All these technological frontiers manifest a subtly paradigm shift in the sphere of postharvest science correction to prediction, generalized protocols to customized management and linear processing to closed loop, intelligent systems. Their further evolution will not only deliver food to the world, but it will also ensure the world that they will serve not only as a guarantee of the quality of the food, but also its safety and sustainability will become the primary concern on the entire cycle of the life of the fresh produce.

### Conclusion

Cucurbitaceous vegetables are an economically and nutritionally significant horticultural commodity but due to the high moisture and thin epidermal structure and continuous metabolic activity following harvest, they are highly vulnerable to rapid quality drop and post harvest losses. The serial review has critically synthesized the existing information of the postharvest physiology of cucurbitaceous vegetables, with the focus on the interdependence of respiration, ethylene sensitivity, transpiration, enzymatic activity, oxidative stress and chilling injury in regulating shelf life and marketability. These physiological and biochemical activities work in species selected way and combine together to define the texture deterioration, colour alteration, nutrient wastage along with vulnerability to microbial harm. The review also emphasizes that single interventions cannot support the effective shelf life extension but should be multi hurdle approaches. Temperature and humidity control, controlled atmosphere storing and modified atmosphere packaging are still basic in inhibiting metabolic activity and loss of water. Meanwhile, new physical and chemical technologies absorb ultraviolet irradiation, heat treatments, high-voltage electrostatic fields, electrolyzed water, ethylene inhibitors, calcium salts, melatonin, essential oils and biological control agents all show some promise in reducing residues and increasing stress tolerance and decay reduction. The development of multi omics solutions, non-destructive methods of sensing, monitoring systems based on the Internet of Things and sustainable packaging materials also give new possibilities to precision in postharvest management and real time monitoring of quality. Going forward, future studies need to find a way of coming up with crop specific, environmentally friendly and economically viable, postharvest technologies that are flexible in different supply chains, especially in areas with limited resources where losses are most pronounced. The enhancement of the interrelation between physiological knowledge, molecular knowledge and clever technologies will be necessary to minimize the postharvest losses, increase the shelf life and facilitate international food security and sustainable agriculture.

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