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SUSTAINABLE POSTHARVEST TECHNOLOGIES FOR EXTENDING CUT-FLOWER VASE LIFE

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ABSTRACT:
Severed from their roots, flowers on the market for sale start the clock on their death. Flowers continue to respire and experience a variety of other stressors as the postharvest treatment and transport begin. This review of the literature interprets 35 studies published between January 1, 2020, and June 20, 2026, on the sustainable technology for postharvest treatment and tool commercialization. Information was categorized by balancing practices, xylem, carbohydrates, ethylene, oxidative stress, microbes, and temperature management along the supply chain. The results showed considerable variance among the treatments by species, cultivar, treatment concentration, harvest maturity, water quality, temperature history, storage length, and microbial load. It was found in some studies that melatonin considerably increased the postharvest vase life of carnations by 10 days and of Alstroemeria by 10 days to just over 20 days. Sage and rosemary oils kept gladiolus stems fresh about 88% and 85% longer, respectively. Active modified-atmosphere packs gave nasturtium blooms three extra days of usable freshness. The most defensible strategy for commercialization is a combination of treatment along the supply chain from sanitation, hydration, cooling, and packaging, followed by care in the retail for the intended purpose (vase). The bioremediation and nanotechnology systems have the most promise for the commercialization for postharvest systems, but worker safety and life patents need to be assessed.

KEYWORDS: postharvest physiology; sustainable preservatives; vase life; cold chain; cut flowers

INTRODUCTION

Cut flowers are highly valuable, globally traded goods in the floral industry. Their selling value mainly depends on appearance and how long they stay fresh after cutting. Deterioration starts soon after harvest because internal life processes continue and microbes can enter exposed stems or multiply in holding water. The microbial infections cause wilting, neck bending, petal and leaf darkening and abscission, failure of buds to open, and the development of foul odors. All of these reduce marketability of the flowers at the various stages of the supply chain and in end use (1–3).

There is also an increasing need to improve post-harvest management for environmental and occupational reasons. While silver thiosulfate, silver nitrate and hydroxyquinoline-based biocides are effective preservative solutions for certain flower species, there is growing concern regarding the safety of these biocides for workers, their persistence in the environment and their regulatory acceptance. As there are significant post-harvest losses in many of the traditional flower crops in India due to lack of proper handling, storage and transport, it is critical that these losses be addressed with the development of safer and more efficient resource alternatives (4). This has created interest in the use of plant extracts and essential oils with a biodegradable carrier and low residue technologies (5).

Cut flowers are severed from their supply of water, but still respire and transpire after being harvested. Postharvest condition is shaped by harvest stage, water cleanliness, storage and transport conditions, xylem function, and stored carbohydrates, among other factors. There are species and cultivar dependent responses to chilling, ethylene, preservatives and pathogens; therefore, a universal approach to post-harvest treatment cannot be applied to every flower species or every supply chain (6,7).

Recent studies have reviewed packing systems of tropical flowers and Heliconia, native ornamental crops, traditional flowers, and natural preservatives (1-5). This review extends that work by linking safer methods with decisions made from harvest through storage, delivery, and final use, while considering the biological limits of each crop. It answers the following questions: What causes the decay of flowers after harvest? Which recent low-impact methods can keep cut blooms usable for longer? How can people across the chain, from growers to buyers, use these methods responsibly?

2. LITERATURE SEARCH STRATEGY AND REVIEW METHODOLOGY

2.1 Search sources and period

A structured narrative review was done to analyze the latest evidence pertaining to sustainable postharvest management of cut flowers. Searches of the literature were carried out between January 1, 2020 and June 20, 2026. Evidence was located through five bibliographic services: Scopus, WoS Core Collection, PubMed, Crossref, and Google Scholar. Full-text and platform searches were also carried out in ScienceDirect, SpringerLink, Frontiers, MDPI, Wiley Online Library, and the ICAR e-publications portal. Backward citation searches of eligible reviews and primary studies were done to supplement the database searches.

2.2 Search strategy

The central search string joined the concepts of crop, outcome, and treatment. These include: ("cut flower*" OR "cut-flower*" OR "floral stem*" OR "cut ornamental*") AND (postharvest OR "vase life" OR "shelf life" OR "flower longevity" OR "postharvest quality") AND (melatonin OR polyamine* OR "essential oil*" OR "plant extract*" OR nano* OR nanoparticle* OR "1-methylcyclopropene" OR "1-MCP" OR "chlorine dioxide" OR "modified atmosphere packaging" OR "cold chain" OR "digital cold chain" OR logistics AND sensor*). The relevant syntax and field tags for each database were used while maintaining the basic Boolean logic.

Additional searches for specific crops were conducted combining postharvest results with the terms rose, carnation, gerbera, tulip, gladiolus, Alstroemeria, peony, tuberose, chrysanthemum, lily, and Heliconia. These terms were combined with xylem occlusion, neck bending, ethylene response, oxidative stress, antioxidant activity, bending, storage, transport, and microbial load. These searches were complemented using scientific and commercial names of crops combined with the terms treatment dose and harvest, storage, temperature, and vase life.

2.3 Eligibility, screening, and data extraction

Peer-reviewed primary studies, recent reviews, and other cold-chain or logistics studies were considered when they provided a specific crop, treatment or handling condition, and at least one postharvest outcome. The selected outcomes included usable duration, bud opening, change in fresh mass, water absorption, microbial levels, response to ethylene, membrane injury, antioxidant condition, color retention, physical strength, storage performance, and supply-chain results. Sources were excluded if they were out of the time frame, did not cover cut-flower postharvest management, had insufficient methods, were duplicates of another entry, or did not provide relevant evidence for sustainability or commercial translation.

Records were assessed by title and abstract for date appropriateness, relevance to cut-flowers, identified a crop, suitability for management, and outcome. The full text was reviewed for presence of treatment and comparator, endpoints, methods, and relevance for commercial and/or sustainability purpose. Data were extracted to an evidence matrix for crop and cultivar, treatment and dose, stage of application, comparator, outcome, postulated mechanism, safety or residue considerations, and commercial relevance.

2.4 Evidence-base profile and synthesis

The final evidence base comprised 35 publications: There were 20 original research studies and 15 review and synthesis pieces or research on cold-chain logistics. Given the variations in crops, formulations, treatment durations, handling conditions, and outcome measures, the synthesis was of a narrative, structured type. The study selection and evidence-base synthesis is summarized in Table 1.

Three relevance filters were applied during the selection of these studies. First, studies related to the balance of water, carbohydrates, ethylene, oxidative stress, microbial activity, stem mechanics, and temperature were given high physiological relevance. Second, studies that showed a reduction of hazardous and/or undesirable substances and/or waste, improved the efficiency and/or the sustainability of resources and/or assessed safer alternatives were given high sustainability relevance. Third, evidence on important decisions from harvest until consumer use received a high commercial-relevance rating.

3. Physiological mechanisms of postharvest deterioration

3.1 Water imbalance and xylem occlusion

Postharvest loss in quality with flowers can be attributed primarily to an imbalance with water. Flowers in transit should have open xylem vessels, as little as possible embolism, low contamination, and prompt transfer of cut stems to the correct holding solution. If there is no turgor pressure, there is a loss of target and the flowers begin to wilt, necks bend, petals and leaves droop and do not fully open. Rose varieties differ greatly in their water balance and in the period for which cut stems remain usable (6,7).

Growth of microorganisms will clog the xylem tissue and ruptured hydraulic failure will result. Water in the vase is a favorable habitat to bacteria, biofilm and extracellular material will clog the xylem tissue; the tissue will be further obstructed by other physiological deposits (8). Stem bending will be less of an issue and water uptake will be improved with the application of nanotechnology and modified silver. Other possible controls include botanical oils, chitosan materials, and oxidants; however, each option requires a separate crop-specific safety review (9-13).

3.2 Carbohydrate depletion

Carbohydrate reserves dwindle due to unrestricted respiration and limited supply from photosynthesis. The soluble sugars are critical for cellular metabolism, petal expansion, bud opening, pigmentation and synthesis of volatiles. Thus, opening and longevity can be improved with the application of sucrose. However, sucrose must be used in combination with sanitation or acidification, since sugar solutions promote microbial proliferation. The application of a composite solution of sucrose and melatonin improved the absorption of water and vase life after storage of peony (14).

3.3 Ethylene signaling and senescence

Ethylene-sensitive flowers display more rapid petal wilting, abscission, inrolling, fading, and yellowing of leaves. The effectiveness of 1-MCP is dependent on concentration, exposure time, temperature, developmental stage, species, and genotype (15). Selenium alters responses to oxides and ethylene and can be variable within taxa; for example, Eremurus species have different responses to ethylene and thus different vase lives (16,17).

3.4 Oxidative stress and structural failure

Wounds, moisture loss, and temperature extremes cause ROS to form and build up in floral tissues. These cause cellular injuries through leakage of membranes and pigments and peroxidation of lipids. Indicators include malondialdehyde, hydrogen peroxide, and electrolyte leakage, along with changes in antioxidant enzyme activities. There is growing interest in using postharvest melatonin treatments to modulate antioxidant activity (18–21). Antioxidants and melatonin regulate stages of the same signaling pathway, however, and therefore, a defined concentration of melatonin is important in designing a low-residue postharvest antioxidant treatment.

Bending of the neck is an indicator of reduced stiffness of stems and dehydration. Neck bending in Gerbera is reduced by melatonin through modulation of the uptake of water, antioxidants, NO, salicylic acid, and ligin (22). Melatonin-capped copper nanoparticles were reported to increase stem stiffness and regulate stem stiffness through the same modulation of lignin and associated physiological traits (23).

3.5 Temperature and handling stress

Temperature impacts up to seven important aspects of the postharvest chain including respiration and transpiration as well as the production of ethylene, the growth of microbes and the stability of membranes. Precooling the harvest is an effective way of slowing the deterioration of the harvest. However, it is critical to apply the appropriate temperature for the specific harvest because the temperature regimes that work for crops from temperate zones may be harmful to those from tropical zones. As a result, long-distance transport requires specification of the temperature as well as humidity, packaging, and monitoring of the temperature along the entire transport segment as opposed to just applying a cold chain (1-3, 24, 25).

Table 2 attempts to bring some order to the overwhelming abundance of literature by consolidating these factors and their sustainable interventions. These constraints interact: blocking microbes can worsen water loss, unregulated growth of microbes can be caused by the supply of carbohydrates and warming can promote the growth of decay in nearly all systems. The matrix should be used as a diagnostic system rather than a tome of disparate factors.

4. Recent advances in sustainable shelf-life extension

4.1 Species-specific cold-chain management

The preservation of quality relies on effective cold-chain management. When heat is rapidly removed from the field, respiration and water loss are slowed. Continuous monitoring helps identify and quantify temperature violations. The management approach for such tools and models is changing from reactive to proactive. However, the models for the perishables will need to be validated for the specific crops of cut-flowers and their distribution routes (24,25).

4.2 Ethylene management

Beyond traditional anti-ethylene treatments, current protocols advocate for the targeted application of 1-MCP to specific crops in combination with ethylene exclusion and the avoidance of physiological stress during harvest and postharvest. 1-MCP is particularly beneficial for sensitive species since it inhibits ethylene perception without leaving a heavy metal residue, but it does not resolve dehydration, blocking, depletion, or abuse. Therefore, it should be used in combination with other appropriate treatments to cool, sanitize, and manage carbohydrates (15-17).

4.3 Melatonin and polyamines

Melatonin has shown a variety of beneficial effects on carnation, rose, tuberose, peony, chrysanthemum, gerbera, and Alstroemeria. Melatonin also improved the postharvest quality of several other species, enhanced the rose's antioxidant activity, and lengthened the carnation's vase life by 10 days (22,26–30). With combined melatonin (100–200 µM) and putrescine (1.5 mM), Alstroemeria remained usable for about 20–21 days instead of 12–13 days (31,32).

Putrescine and polyamines aid in controlling senescence and the resulting oxidative responses. Alstroemeria showed positive results with the combination of melatonin and putrescine, while gerbera showed improvement in vase life and antioxidant activity with the use of spermine and related compounds (31–33).

4.4 Essential oils and plant extracts

The extraction of plants and oils both contain scavenging and antimicrobial properties. Using sage oil at 0.15 g/L alongside rosemary oil at 0.10 g/L kept gladiolus stems fresh 88.16% and 84.76% longer, respectively; both treatments also lowered microbial load and oxidative harm. The use of these plant extracts commercially, depends on the stability of the emulsion, solubility, odour, standardization of the active ingredients, phytotoxicity, the stability during storage and price.

4.5 Nanotechnology-based treatments

Although antimicrobial control and targeted delivery can be enhanced by nanotechnology, concerns regarding safety of residue, worker exposure, phytotoxicity and the fate of nanotechnology in the environment continue to be a critical challenge. In gerbera, nano-silver has lowered bacterial multiplication and reduced stem bending (9, 10). For tulips, copper nanoparticles (Cu-NPs) improved postharvest performance and produced usable periods of 15.56 and 16.33 days across two seasons, compared with untreated flowers (11). Studies have also examined nanochitosan carrying melatonin for delayed petal ageing and melatonin-coated Cu-NPs for stronger gerbera stems (23, 34).

4.6 Modified atmospheres and oxidizing treatments

In long-distance floriculture, packaging that reduces water loss and regulates respiration becomes essential. With active modified-atmosphere packaging at 4 °C, nasturtiums gained 4 days to their shelf-life and improved color with a 35% retention of phenolics (35). While the end use of edible flowers differs from ornamental cut flowers, respiration control, moisture retention, and respiration control packaging, and temperature control are applicable to both. Chlorine dioxide has been shown to delay peony senescence by reducing microbial colonization and oxidative injuries, however, for it to be applied as a routine practice, the concentration, duration of exposure, and tolerance of the crop as well as the safety of the workers has to be determined (13).

4.7 Mechanism-based treatment selection

The key task is not to identify one additive that performs best on its own. Instead, suitable agents should be combined to address the main cause of loss in a particular crop and distribution route. Pilot studies should include control for cultivar, season, stem length, harvest maturity, duration of transport, water quality, microbial load, temperature history, and packaging. Recent experimental evidence is provided in chronological order in Table 3. Complementary mechanisms are described in these studies. Melatonin and polyamines help with balance and protection as antioxidants. Nanoparticles and essential oils help reduce microbial blockage. Modified-atmosphere packaging helps slow respiration and the loss of water. Commercial protocols should therefore be designed for the crop, its growth stage, and the conditions of its supply route.

5. Commercial application and implementation strategy

5.1 Grower and packhouse practices

Commercial translation can rarely be achieved by a single definition. When it comes to formulating a reproducible protocol, decisions will need to be made concerning crop and cultivar, harvest stage, stem length, harvest, (and post-harvest) hygiene, quality of water, duration of hydration, composition and duration of the pulse, packing, the temperature of transport, duration of storage, and recommended care. Within the realm of applied science, it has been noted that lab-based treatments will fail in the field when the above are not addressed (1,2,5,15,24,25).

In the grower and packhouse communities, the priority becomes the least cutting damage, the cutting practice, and harvest maturity; removal of field heat and hydration are also prioritized. Harvesting sprouts from water with a high microbial count may result in a failed attempt to preserve the sprouts. In some regions, the combination of disciplined sanitation, acidified water, and good cooling will provide more value than the early use of elaborate additives (6,8–10).

5.2 Exporter and wholesaler operations

Exporters and wholesalers need to set storage and transportation conditions based on crop tolerance. Using a single ‘cold chain’ rule is inappropriate. For instance, tropical flowers and some native foliage will be damaged with exposure to temperatures that are appropriate for storage and transport of roses and carnations. Packaging should minimize moisture loss but should also prevent condensation and the growth of disease. Package permeability should match the breathing activity of the flowers and foliage, the moisture level, and the buds’ ability to open after unpacking (2,3,24,25,35).

5.3 Retail and consumer vase care

The design of retail and consumer solutions should incorporate simplicity and safety while being hard to misuse. Rather than complicated formulations, adherence is more likely to happen to the use of premeasured sachets, labeled hydration products, cleaned buckets, an ice pack with a cool display, and regular water replacements, as well as the removal of broken stems. For retail use, the extracts and oils of plants will need to have a standardized active ingredient(s), quality and type of emulsion, solubility, fragrance, phytotoxicity, and stability in storage (5,12,13).

5.4 Sustainability and digital traceability

Just extending vase life is not a good indicator of sustainability. There are other factors to consider such as burden and residue of the chemicals used, exposure to workers, packing materials, energy consumption, waste, rejection, customer satisfaction, and cost. Use of temperature and humidity sensors, along with QR-based traceability and predictive vase life models will help to document whether a batch was kept within its quality window and help to locate losses (24,25).

Table 4 shows a staged commercial implementation matrix with references. Reliable sanitation and hydration along with species-specific temperature control form the basis. The use of advanced additives and biodegradable delivery systems along with modified atmospheres and digital platforms should be considered only after the basic handling chains are in place and stable, and the expected quality benefits justify the cost.

6. Integrated sustainable management framework

6.1 Diagnostic principle

The first step of integrated management is to recognize the dominant constraint. Supplementing carbohydrates does not solve microbial occlusion; ethylene and carb depletion cannot be reversed with supplemental sucrose and may even worsen microbial contamination. As such, balanced Water management, Microbial control, Metabolic moderation, Hormonal control, and management of Oxidative stress (WMMHOS) should be applied in an order that is appropriate to the supply chain and specific to the crop. (6–25).

6.2 Four management modules

The system consists of 4 linked modules. The first module, Water Balance, includes sanitation, recutting, antimicrobial treatment, hydration control, pH adjustment, and uptake monitoring. The second module, Metabolic Moderation, contains precooling, storage, and modified atmosphere and humidity control of different plant species. The third module, Biochemical Protection, comprises melatonin, polyamines, vitamin C and related substances, plant extracts, and essential oils. The last module, Signal Control, includes ethylene removal, 1-MCP, and control of the interactions of ethylene, nitric oxide, salicylic acid, and 6–25.

6.3 Mechanism-to-application pathway

Figure 1 shows how harvest injury and supply-chain stressors cause multiple problems, including hydraulic failure, oxidative injury, disruption, and degradation of membrane and physiological stability, and ultimately, a reduction in visible quality. Figure 2 shows how these challenges transform and extend through the commercial chain from harvest sanitation and rapid pre-cooling to hydration and physiological manipulation and packaging, through the cold chain to vase care at retail. Figure 3 attempts to map out the constraints in diagnostics, and demonstrates possible interventions considering safety, cost, and commercially viable options.

The framework allows for an explanation of the variability in treatment effects. For example, nanoparticles are effective against microbial blockage, but do not replenish carbohydrates. In another example, melatonin may be beneficial in reducing oxidative injury and membrane leakage but may need to be used in conjunction with sugar and an antimicrobial when bud opening and microbial contamination are concurrent issues. Essential oils have a clear positive effect at low concentrations, but may become phytotoxic at high concentrations. Modified atmospheres may help support storage, but means of compensation are not available for a batch that enters the supply chain in a hot, wet, mechanically injured, contaminated state (5,9–15, 18–25).

7. Research gaps and future directions

7.1 Standardization and reporting

Current studies vary in terms of cultivars and all the typical factors like harvesting, stem length, solution, temperature, and quality, as well as the factors that influence vase life, like humidity, duration, storage, light, and endpoint. Future studies include all the environmental factors listed, and should also include relative humidity, water chemistry, solution renewal, and microbial factors, along with endpoint definitions. Reporting in this way should help comparability and synthesis of evidence and help with conducting meta-analyses (1,2,5,10,15,20,21).

7.2 Multi-location and supply-chain validation

Numerous new treatments have shown promise, but so far only in controlled lab settings. Testing should include the farm, the packhouse, transport, the whole sale and retail trade, as well as the consumer, and should include realistic mixed loads, temperature, condensation, and display and transport vibrations. Systems that include nanotechnology will require a residue, phytotoxicity, worker-safety and environmental-risk assessment prior to their adoption (5, 9-11, 23, 34).

7.3 Sustainability assessment

The real postharvest benefits of using energy-hungry methods to obtain botanical compounds must be taken into consideration. The same goes for refrigerated supply chains. While they could diminish product waste, refrigeration increases energy consumption. Future research should look at the tradeoffs of vase life and the factors mentioned (3, 5, 24, 25).

7.4 Cultivar-specific physiology and breeding

Breeding and postharvest physiology should be combined because of the differences among genotypes in ethylene sensitivity, stem strength, hydraulic conductance, antioxidant capacity, chilling tolerance, and disease resistance. When more cultivars are developed, postharvest traits need to be evaluated along with yield, uniformity, stem length, flower color, fragrance, disease resistance, and market demand (7,22).

7.5 Formulation science and data integration

Numerous challenges exist for multi-component formulations of melatonin, plant extracts, essential oils, and nanoparticles. For melatonin, sensitivity to light and the need for precise dosing with nanoparticles pose challenges to formulation. As for plant extracts and essential oils, the presence of variable components complicates formulation. Some formulation challenges can be addressed with the use of biodegradable carriers, controlled-release systems, and low-cost validated formulations. Priority areas also include shelf-stable formulations. Small- and large-scale growers (5,20,21,24,25,34) may benefit from the application of dynamic shelf-life models that account for variations in cultivars, harvesting times, and user/consumer driven variations in water quality and temperature, as well as humidity, transport duration, and retail conditions.

8. CONCLUSION

A sustainable solution requires treatment selected by the cause of deterioration, rather than one product for every cut flower. Depending on the main crop and the restrictions of the supply chain, different combinations of sanitation, rapid hydration, species-specific pre-cooling, targeted management of ethylene and oxidative stress, appropriate packaging, and monitored retail care should be used. There is a lot of interest in the use of certain melatonin, polyamines, plant-based antimicrobials, and nanotechnology, but their commercial use depends on a lot of factors. These include the ability to produce the technology in a cost-effective manner, and most importantly, the safety of the product for the workers and consumers while leaving no residue. Other factors include the ability to provide technology for real field applications, the ability to provide logistics on a just in time or order basis, and an optimal biodegradable formulation. Standardized reporting is important. All of these factors must be present to minimize losses while maximizing quality and sustainability.

Tables

Table 1. Study selection and final evidence-base profile

Study-selection element	Final evidence-base profile	Basis
Search period	1 January 2020 to 20 June 2026	Section 2 search protocol
Selection procedure	Initial review of titles and summaries, followed by evaluation of complete articles	Selection rules described in Section 2.3
Sources in final evidence base	35 publications	Final reference list and evidence matrix
Primary experimental studies	20 publications	Evidence matrix
Reviews, syntheses, and cold-chain/logistics sources	15 publications	Evidence matrix
Analytical approach	Structured narrative synthesis	Heterogeneity in crops, treatments, handling conditions, and outcomes

Table 2. Principal physiological constraints in cut-flower postharvest life and sustainable intervention points

Constraint	Mechanistic basis	Typical quality symptom	Useful indicator	Sustainable management option	Key references
Water imbalance and xylem occlusion	Air embolism, physical or physiological plugging, microbial biofilms, poor recutting, and high transpiration	Wilting, neck bending, poor bud opening, and reduced fresh weight	Change in fresh mass, water absorption, xylem flow, and cloudiness of the holding solution	Clean tools, recutting, prompt hydration, acidified water, and compatible antimicrobial treatment	(6–10)
Carbohydrate depletion	Continued respiration after detachment, restricted photosynthesis, and prolonged storage	Incomplete opening, weak color, reduced fragrance, and rapid senescence	Soluble sugars, respiration rate, and flower-opening index	Sucrose pulsing or holding solutions combined with sanitation; optimized composite solutions	(6,14)
Ethylene sensitivity	Stress-driven ethylene release and signal transfer through its receptors	Wilting or inward rolling of petals, petal drop, and yellow leaves	Ethylene emission, ACC synthase/oxidase activity, and response to exogenous ethylene	1-MCP, low temperature, ethylene exclusion, and stress minimization for sensitive species	(15–17)
Oxidative stress	ROS accumulation, lipid peroxidation, and antioxidant-system exhaustion	Petal browning, discoloration, membrane leakage, and loss of turgor	MDA, H_2O_2, electrolyte leakage, SOD, CAT, APX, and POD	Melatonin, polyamines, plant extracts, essential oils, and other antioxidant-supporting approaches	(18–23,26–34)

Microbial contamination	High microbial load in vase water and stem bases; nutrient-rich exudates and biofilm formation	Odor, xylem blockage, turbid solution, and reduced vase life	CFU counts, biofilm observation, stem-end microscopy, and solution clarity	Sanitation, acidifiers, essential oils, chlorine dioxide, nano-silver, or nano-copper where safety is established	(8–13,34)
Temperature and handling stress	Field heat, delayed cooling, chilling injury, condensation, and rough handling	Bruising, leaf blackening, petal damage, and uneven opening	Temperature and humidity logs, respiration, and visual-quality score	Species-specific cold chain, MAP, humidity management, sensors, and insulated logistics	(1–3,24,25, 35)

Table 3. Recent experimental evidence for sustainable vase-life extension technologies in chronological order

Year	Flower/species	Treatment	Reported response	Main mechanism	Citation
2021	Gerbera "Real"	Nano-silver pretreatment	Reduced stem bending and improved water uptake	Suppression of dominant bacteria at stem ends and reduced xylem blockage	(9)
2022	Carnation	Melatonin postharvest treatment	Vase life extended by 10 days compared with the control	Improved antioxidant protection and delayed senescence	(26)
2024	Gladiolus spikes	Sage essential oil 150 mg L^{-1}; rosemary essential oil 100 mg L^{-1}	Freshness period rose by 88.16% with sage oil and 84.76% with rosemary oil	Lower bacterial count, H_2O_2, and MDA; improved water uptake and antioxidant activity	(12)
2024	Peony after 30 days of cold storage	0.5% sucrose + 0.5 mM melatonin; optimized composite vase solution	Vase life increased from 4.7 to 6.7 days with the basic solution and to 7.5–8.9 days with the optimized solution	Improved water absorption, membrane protection, and antioxidant capacity	(14)
2024	Edible begonia, nasturtium, and viola	Active MAP at 4 °C	Nasturtium shelf life increased from 4 days in passive MAP to 7 days in active MAP	Lower respiration, improved color retention, and phenolic preservation	(35)
2025	Tulip	30 mg L^{-1} copper nanoparticles; 7.5 mg L^{-1} chitosan nanoparticles	Copper nanoparticles produced vase lives of 15.56 and 16.33 days in two seasons; chitosan nanoparticles also improved longevity	Antimicrobial action, fresh-weight maintenance, and reduced ethylene-related deterioration	(11)
2025	Alstroemeria "Amatista"	100–200 µM melatonin combined with 1.5 mM putrescine	Usable display duration grew from roughly 12–13 days to about 20–21 days	Improved relative water content, solution uptake, and membrane stability; reduced oxidative damage	(31,32)
2026	Gerbera "Pink Elegance"	Melatonin 50–400 µM; optimum near 300 µM	Reduced neck bending and extended vase life	Improved water uptake, antioxidant enzymes, nitric oxide, salicylic acid, and lignin accumulation	(22)

Table 4. Commercial implementation matrix for sustainable cut-flower postharvest management

Supply-chain point	Practical intervention	Relative adoption cost	Expected commercial value	Key adoption condition	Key references
Grower or farm level	Harvest-stage selection; clean tools; immediate hydration; shade; rapid field-heat removal	Low to medium	Lower initial stress and microbial load; improved uniformity	Training and simple monitoring checklists	(1,4,6,8)

Supply-chain point	Practical intervention	Relative adoption cost	Expected commercial value	Key adoption condition	Key references
Packing house	Grading, recutting, pulsing, acidified water, sucrose-biocide balance, and 1-MCP for sensitive flowers	Medium	Improved opening, reduced ethylene damage, and stronger export readiness	Prevention of cross-contamination and unsuitable universal recipes	(6,8,14, 15)
Exporter or wholesaler	Species-specific cold chain, MAP, humidity control, data loggers, and ethylene avoidance	Medium to high	Better transport quality and fewer claims	Investment and correct temperature setting by crop	(1–3,24,25, 35)
Retail florist	Clean buckets, cool display, premeasured vase solution, water replacement, and removal of damaged stems	Low to medium	Longer display life and improved customer satisfaction	Staff compliance and routine sanitation	(5,6,12, 13)
Advanced product developers	Essential-oil emulsions, nanochitosan, melatonin formulations, and biodegradable delivery systems	High	Differentiated sustainable products and access to residue-sensitive markets	Toxicology, regulatory review, shelf stability, and cost validation	(5,11,12,20,21,23,34)
Digital supply-chain managers	IoT sensors, QR traceability, predictive vase-life models, and cold-chain dashboards	High	Traceable quality, data-based logistics, and reduced hidden temperature abuse	Data standards, connectivity, and integration with commercial decisions	(24,25)

Figures

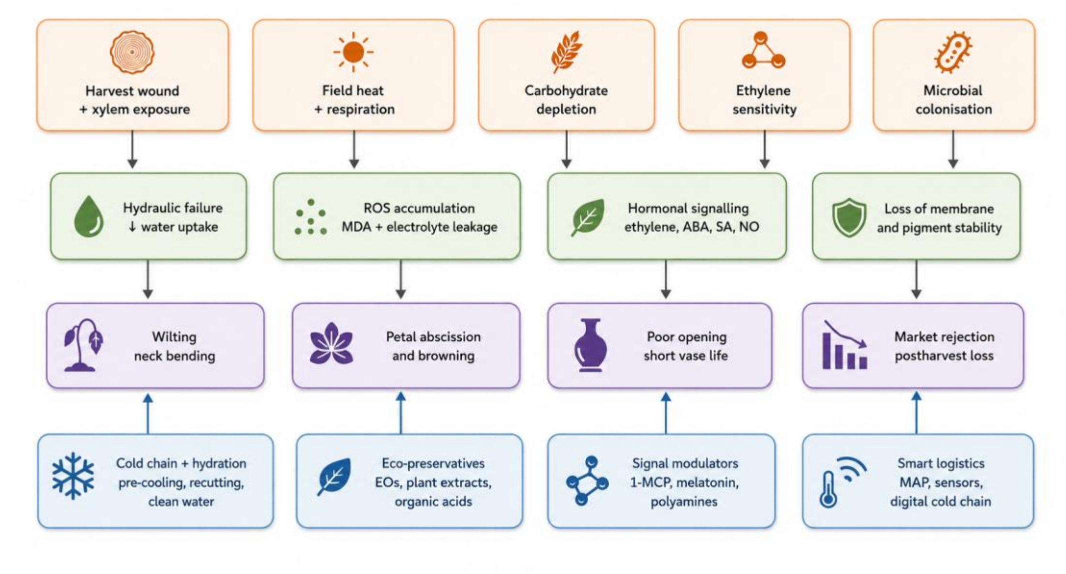

Fig. 1. Model of processes involved in postharvest senescence of cut flowers. Postharvest factors such as harvesting, field heat, depletion of carbohydrates, microbial infection, and ethylene sensitivity converge at hydraulic failure, oxidative damage, and disruption of the balance of hormones and membrane stability. Source: Prepared by the authors with no external image copyrighted needed from literature cited in sections 3 and 4.

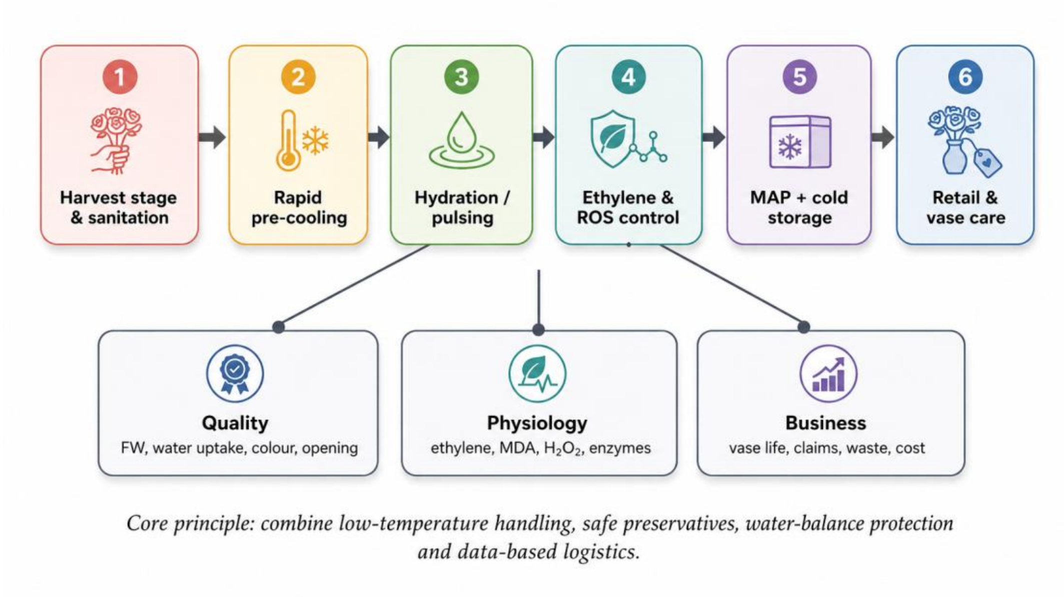

Fig. 2. Eco-friendly commercial model of the postharvest chain of cut flowers. Combining sanitation, quick cooling, hydration, storage, transport, and present-day vase care helps keep cut flowers in good condition while meeting commercial and scientific postharvest needs. Source: Prepared by the authors with no external image copyrighted needed from the literature cited in sections 4 to 6.

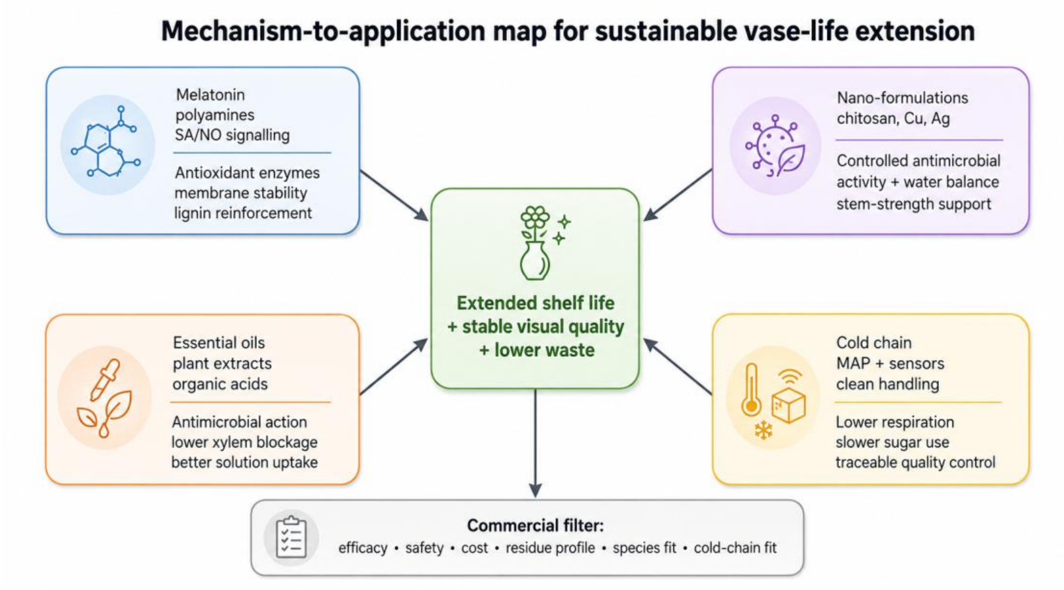

Fig. 3. Linking causes with practice: a sustainable route to longer-lasting cut flowers. An integrated approach emphasizing the dominant physiological constraints, interventions, and commercial viability. Source: Prepared by the authors with no external image copyrighted needed from the literature cited in sections 3 to 6.

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