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REVIEW ARTICLE

Aloe vera gel as a natural solution for sustainable plant disease management and postharvest longevity in fruit crops amidst climate shifts

Lakshmi S[1], Ga Dheebakaran[1*], S Kokilavani[1], A Senthil[2] & C Kavitha[3]

[1]Agro Climate Research Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Turmeric Research Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - gadheebakaran@tnau.ac.in

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Abstract

Climate variability and increasing postharvest losses have intensified the need for sustainable alternatives to synthetic pesticides and preservatives in horticultural systems. Conventional postharvest management approaches, while effective to some extent, face critical limitations; chemical treatments raise concerns over residues and human health, while many bio-based coatings such as starch, gum arabic and essential oils suffer from weak barrier properties, rapid degradation or inconsistent antimicrobial performance. This review evaluates the potential of *Aloe vera* gel extract as a natural, eco-friendly solution for plant disease management and postharvest quality preservation in fruits and vegetables, particularly under the pressures of climate-induced stresses. Rich in bioactive compounds such as acemannan, anthraquinones, flavonoids and saponins, *A. vera* gel demonstrates strong antimicrobial, antioxidant and immunomodulatory activities. Unlike other coatings, it not only forms an effective edible film but also contributes functional prebiotic and therapeutic benefits, making it uniquely multifunctional. It acts both as a biocontrol agent and a protective edible coating, delaying spoilage by inhibiting fungal and bacterial pathogens, reducing respiration rates and preserving textural and nutritional quality. Moreover, the integration of *A. vera* gel into composite coatings with biopolymers such as chitosan and alginate significantly enhances barrier properties and antimicrobial efficacy. Its dual role in both prevention and treatment of postharvest diseases, relevance in climate-resilient agriculture and compatibility with biodegradable packaging systems highlight its potential as a sustainable solution. Emphasis is also placed on its safety, affordability and role in promoting circular agro-economies, which are farming systems that minimize waste by reusing agricultural by-products and promoting resource efficiency. Future prospects lie in the standardization of formulations, elucidation of underlying mechanisms and field-level validation to facilitate its widespread adoption in postharvest management.

Keywords: *Aloe vera* gel extract; climate resilience; horticulture crops; postharvest management; shelf-life enhancement

Introduction

The Green Revolution transformed agriculture through high-yield, input-responsive varieties, yet it also led to reduced genetic diversity and widespread monoculture systems. These shifts have made crops increasingly vulnerable to diseases and pests, a situation now worsened by the accelerating effects of climate change (1). Rising temperatures, fluctuating humidity and irregular rainfall patterns foster ideal conditions for pest and pathogen proliferation, while simultaneously disrupting postharvest physiology by hastening ethylene biosynthesis, respiration and enzymatic degradation in fresh produce (2, 3). Studies have shown that crops such as tomatoes, bananas and green chilies undergo rapid spoilage under elevated temperature and humidity stress, contributing to significant postharvest losses (4). Climate-induced abiotic stress also compromises the efficacy of synthetic fungicides and pesticides, further fueling the emergence of resistant pathogens. For example, elevated storage temperatures have been shown to reduce the effectiveness of thiabendazole treatments against *Penicillium digitatum* in citrus fruits, resulting in higher decay rates (5). Similarly, fluctuations in relative humidity alter the persistence of fungicide residues on grape berries, lowering their protective efficacy against *Botrytis cinerea* (6). Unpredictable rainfall patterns also dilute foliar-applied pesticides, leading to reduced field efficiency and contributing to the rapid development of resistant strains in crops such as rice and wheat (7). Moreover, the prolonged use of synthetic agrochemicals raises concerns over environmental toxicity, residue accumulation and disruption of beneficial soil microbiota, prompting consumers and policymakers to seek safer, eco-friendly alternatives. Climate-induced abiotic stress also compromises the efficacy of synthetic fungicides and pesticides, further fueling the emergence of resistant pathogens (8).

In this context, research has increasingly turned toward bio-based preservation strategies such as edible coatings, plant-derived antimicrobials and biopolymer composites, which offer safer and more sustainable alternatives to conventional chemicals. Among these natural derived solutions, *A. vera* gel stands out because of its unique multifunctionality, it not only serves; as a protective coating but also contributes antimicrobial, antioxidant and physiological benefits that directly address climate-related postharvest challenges. *A. vera* gel sourced from *Aloe barbadensis* Miller, has emerged as a promising multifunctional agent for sustainable plant protection and shelf-life extension (9). Rich in compounds such as acemannan, glucomannan, flavonoids, saponins and phenolics, *A. vera* gel exhibits notable antimicrobial, antioxidant and moisture retaining activities (10). When applied as an edible coating or postharvest dip, *A. vera* gel has shown significant efficacy in controlling spoilage microorganisms such as *Penicillium*, *Botrytis* and *Colletotrichum*, while also delaying ripening and minimizing physiological weight loss in both climacteric and non-climacteric fruits (11). Furthermore, its natural film-forming properties help regulate gas exchange and moisture loss, crucial for mitigating climate-related deterioration. Aloe-based formulations have proven successful under variable temperature regimes and are easily integrable into low-tech handling systems, making them especially relevant for smallholder systems facing unpredictable climates (12). This review comprehensively explores *A. vera* gel's role as a natural, sustainable biopreservative in the context of climate-resilient horticultural practices, highlighting its active compounds, mechanisms of action, application methods and potential integration into circular, climate-smart food systems.

Bioactive components of *A. vera* gel

A. vera gel contains a complex array of bioactive substances. Notably, it includes acetylated polysaccharides such as acemannan and glucomannan, phenolic compounds such as aloin and aloe-emodin, vitamins, enzymes like peroxidase and essential minerals (13). Acemannan, a β-(1→4)-linked acetylated polymannose, constitutes up to ~60 % of the polysaccharide fraction of the gel, as confirmed by chromatographic and structural analyses in original studies (14). It has been shown to form protective films, modulate immune responses and inhibit microbial proliferation. However, studies focusing on whole-gel extracts have demonstrated that the synergistic action of all components enhances antioxidant and antimicrobial properties more effectively than any single compound alone (15).

The structural features of acemannan, particularly its β-1,4 -linked mannose backbone and acetyl groups, are responsible for its moisture-retention ability, high viscosity and free radical scavenging capacity (16). Alongside this, phenolics and anthraquinones exhibit broad-spectrum antimicrobial activity by disrupting microbial membranes and neutralizing reactive oxygen species. Additionally, the presence of vitamins and enzymes further enhances the gel's total antioxidant potential, supporting its role as a bioactive edible coating that can help preserve the sensory and nutritional quality of perishable produce.

The composition and efficacy of *A. vera* gels are influenced by several factors, including leaf maturity, plant genotype, geographic origin and the extraction method employed (17). Comparative analyses of aqueous, ethanolic, microwave-assisted and chitosan-enhanced extractions have reported significant differences in polysaccharide and phenolic concentrations, which directly correlate with antimicrobial potency (13). Aloe-based edible coatings, often combined with chitosan, alginate, starch or nanomaterials such as titanium dioxide (TiO_2) have been shown to extend the shelf life of crops like tomatoes, blueberries, figs, papayas and guava by 10 to 19 days during cold storage while maintaining key quality attributes like firmness, colour and bioactive content (18). Nonetheless, standardization in *A. vera* cultivation, gel extraction and processing remains critical to ensure consistency and reproducibility for successful commercial application (19). Fig. 1 represents the mode of action of *A. vera* gel in postharvest protection.

Mechanism of action

A. vera gel exhibits a powerful combination of antimicrobial, antioxidant and physical barrier properties, making it highly suitable as a natural postharvest treatment, particularly as rising temperatures and humidity under climate change increase the vulnerability of fresh produce to spoilage (20). Its effectiveness lies in its rich composition of bioactive compounds, including phenolics, anthraquinones, saponins and key polysaccharides such as acemannan and glucomannan (21). These compounds act synergistically to disrupt microbial cell membranes, increase permeability and trigger oxidative stress, which ultimately leads

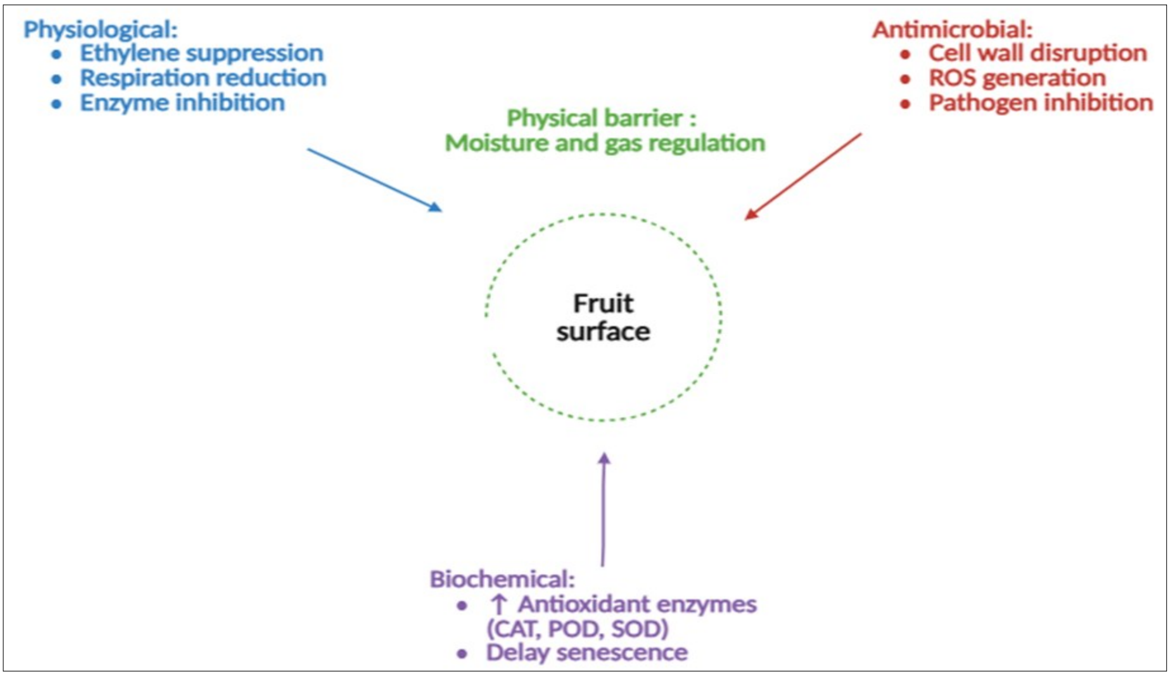

Fig. 1. Mode of action of *Aloe vera* gel in postharvest protection.

to cellular dysfunction and microbial death (22). Numerous studies have confirmed *A. vera*'s broad-spectrum activity against pathogens like *E. coli*, *Salmonella* spp., *Penicillium* spp. and *B. cinerea,* organisms that frequently colonize fruits and vegetables postharvest, especially under stress conditions exacerbated by climate variability (23). The naturally low pH of *A. vera* enhances these effects by impeding microbial quorum sensing and biofilm development, making it even more effective in preserving the surface hygiene of produce (24).

Beyond its antimicrobial action, *A. vera* gel forms a semi-permeable film when applied to fruit or vegetable surfaces, reducing respiration rate, ethylene production and water loss, key factors responsible for accelerating ripening and senescence. These physiological benefits are critical under rising postharvest temperatures, where deterioration occurs more rapidly (25). Across multiple studies, Aloe coatings have consistently delayed ripening and preserved quality by regulating biochemical processes. For example, strawberries stored at 1 °C retained higher antioxidant activity and showed reduced spoilage for over 20 days, while tomatoes coated with 10 % Aloe gel maintained firmness and nutritional quality under cold storage (26). Rather than crop-specific outcomes, these trials collectively demonstrate Aloe's ability to extend both storage duration and nutritional value across different fruit types.

In addition to delaying ripening, Aloe treatments suppress cell-wall–degrading enzymes such as polygalacturonase, pectin methylesterase and cellulase, thereby minimizing softening and browning. Simultaneously, they enhance antioxidant defenses by elevating activities of catalase, peroxidase, superoxide dismutase and ascorbate peroxidase, collectively reducing oxidative stress and delaying senescence. For instance, *A. vera* gel-coated persimmon fruit showed significantly reduced PG, PME and CEL activity, along with a 1.25–1.43-fold increase in CAT and POD over a 20-day storage period and 1.19-fold higher SOD activity compared to controls (27). Similarly, Aloe coated guava fruit displayed elevated CAT, SOD and APX activities under ambient storage conditions (9). These dual biochemical effects (enzyme inhibition + antioxidant induction) highlight Aloe's broad-spectrum action.

Importantly, Aloe gel has proven effective in both climacteric (tomato, papaya, guava) and non-climacteric (strawberry, grape, litchi) fruits, with storage life extended by 10–20 days depending on commodity and treatment combination. For instance, Aloe combined with putrescine preserved firmness and reduced decay in grapes, while applications in papaya, blueberries and litchi consistently prolonged marketability (28). Thus, rather than isolated case studies, the evidence points to Aloe gel as a versatile, climate-resilient coating suitable for diverse horticultural systems.

The effectiveness of *A. vera* gel is further enhanced when integrated with other natural compounds. Incorporating it with chitosan, starch or essential oils improves film-forming strength, adherence and barrier properties, while the addition of nanoparticles like TiO_2 or calcium chloride boosts antimicrobial and antioxidant action (29). Such enriched formulations have shown promising results in maintaining postharvest quality under variable climate conditions, providing a safe and sustainable alternative to synthetic chemicals. By combining antimicrobial, physiological and biochemical modes of action, *A. vera* gel emerges as a highly adaptable tool for extending the shelf life of horticultural produce in climate-sensitive supply chains (30). Table 1 represents the multifunctional mechanism of *A. vera* gel in postharvest protection amidst climate shifts.

Preventive and curative action

A. vera gel serves as both an effective preventive and post-infection curative measure, a duality that is increasingly vital as climate change intensifies postharvest challenges. Elevated temperatures and high humidity, hallmarks of shifting climate patterns favour rapid microbial growth on fresh produce, reducing shelf life (39). In controlled inoculation trials, fruits treated with Aloe gel at 6, 12 or 24 hr after pathogen challenge exhibited significantly smaller lesion sizes and delayed decay. For example, strawberries sprayed 12 hr post-inoculation with *B. cinerea* showed a 65 % reduction in rot incidence, while tomatoes treated after *Alternaria alternata* exposure-maintained firmness 30 % longer than controls. Similar protective effects have been observed in grapes against *Penicillium expansum* and in citrus against *Penicillium digitatum*, highlighting the practical value of *A. vera* when applied as a postharvest dip or spray under warm and humid conditions (40).

Field-based storage simulations reveal *A. vera* gel's curative strength under real-world postharvest regimes. At ambient warehouse temperatures (18 °C-22 °C), Aloe coated strawberries and cherries retained higher levels of ascorbic acid and showed 50 % less spoilage over 10 days compared to untreated fruit (41). Under fluctuating cold-chain conditions, where produce experiences cycling between 2 °C and 12 °C, a common consequence of energy-saving or equipment failure Aloe gel coatings at concentrations of 75 %-100 % effectively reduced water loss by 40 % and maintained

Table 1. Multifunctional mechanisms of *Aloe vera* gel in postharvest preservation under climate stress

Steps of mechanism	Action / mechanism	Details	Reference
1	Antimicrobial action	Bioactive compounds (phenolics, anthraquinones, saponins, acemannan and glucomannan) disrupt microbial membranes, increase permeability and induce oxidative stress.	(31)
2	Antifungal and antibacterial spectrum	Effective against *E. coli*, *Salmonella* spp., *Penicillium* spp., *B. cinerea*, etc., common in climate-stressed produce.	(32)
3	pH-mediated activity	Aloe gel's natural low pH inhibits quorum sensing and biofilm formation in pathogens.	(33)
4	Physical barrier formation	Forms a semi-permeable film that regulates moisture and gas exchange, slowing ripening and senescence.	(19)
5	Respiration and ethylene reduction	Coatings reduce ethylene production and respiration rate, especially under heat stress.	(34)
6	Enzyme inhibition	Inhibits softening enzymes like polygalacturonase and cellulase responsible for tissue breakdown.	(35)
7	Activation of defense enzymes	Increases catalase, peroxidase and SOD activities, improving oxidative stress resistance.	(36)
8	Integration with other coating agents	Combination with chitosan, starch, essential oils and TiO_2 improves coating properties and antimicrobial efficacy.	(37)
9	Extension of shelf life	Tomatoes, strawberries, papaya, grapes, blueberries and litchi showed shelf-life extension of 10-15 days.	(38)

colour and texture in pears and kiwifruit for up to 21 days (42). These findings are especially relevant as rising global temperatures and extreme weather events disrupt traditional cold-chain protocols, emphasizing the need for adaptive postharvest treatments (43).

Emerging research is exploring internal diffusion of Aloe components such as acemannan, glucomannans and phenolic glycosides through the fruit cuticle to target latent infections (44). Biochemically, acemannan and glucomannan interact with fungal cell membranes, disrupting lipid bilayer integrity, increasing ion leakage and triggering membrane lipid peroxidation. Phenolic compounds like aloin and aloe-emodin generate reactive oxygen species (ROS) within microbial cells, leading to oxidative stress, protein oxidation and DNA fragmentation. In host tissues, these compounds activate plant defense-related enzymes, including phenylalanine ammonia-lyase (PAL), catalase and peroxidase, strengthening cell wall lignification and scavenging excess ROS. Preliminary studies indicate that Aloe-treated apple and mango tissues show reduced incidence of latent Colletotrichum appressoria development, suggesting partial penetration of active compounds into epidermal layers (45).

Additionally, combining Aloe gel with biopolymers like chitosan, starch or alginate enhances film viscosity and adherence, further improving curative efficacy when climate fluctuations compromise barrier integrity. These multifaceted actions, including prevention of new infections, mitigation of established disease and activation of internal defenses, demonstrate *A. vera* gel's adaptability as a natural postharvest treatment in a warming world (46).

Post-harvest diseases management

A. vera gel demonstrates remarkable benefits in stabilizing produce quality amid postharvest thermal stress, a growing challenge as climate change drives frequent heat spikes during transportation and storage. In mangoes and avocados kept at 12 °C-28 °C, Aloe gel coatings reduced ethylene release by up to 20 %, slowing overripening and maintaining shelf value under warm handling conditions that simulate the temperature surges increasingly observed in tropical supply chains (47). Likewise, persimmons treated with Aloe maintained soluble solids and acidity levels by ~15 % during fluctuating 18 °C-30 °C storage cycles, conditions mimicking heatwave-driven variability during short-term storage, thereby protecting flavor and texture despite thermal variability. Such results highlight Aloe gel's role in buffering temperature-induced deterioration and preserving quality in climate-stressed produce (48).

Field trials in tropical and subtropical zones further validate Aloe's climate-adaptive properties. Bananas treated with Aloe gel during equatorial shipments averaging 24 °C–32 °C and 85 %–90 % relative humidity experienced 25 % less chilling injury and retained skin integrity throughout 14-day shipping, demonstrating resilience against high humidity and heat exposure, characteristic of climate-stressed export routes (49). In apples exposed to intermittent cold-chain temperature failures (shifting between 2 °C-12 °C), coatings blending Aloe with natural waxes reduced superficial scald by 60 % and preserved antioxidant levels in the peel, mitigating damage from cold-chain breakdowns that are expected to rise with extreme weather and power disruptions (41).

Beyond surface-level preservation, Aloe acts as an effective carrier for climate-resilient antimicrobials, tailored to specific pathogen–produce systems. Bananas treated with Aloe lemongrass nanoemulsions exhibited a 55 % reduction in *Colletotrichum musae* incidence under 28 °C-30 °C conditions, representing an adaptive solution where warming climates intensify fungal infections (50). Similarly, in pepper storage conditions involving abrupt cooling to 5 °C followed by sun exposure, coatings combining Aloe with cinnamon oil effectively suppressed *Phytophthora capsici* while preserving the pungency of 'Habanero' peppers, an example of protection under the kind of sudden temperature fluctuations projected to increase with climate instability (51).

Moving into active packaging applications further demonstrates the value of Aloe integrated coatings in managing moisture and microbial growth during transport. For instance, Aloe-alginate sachets placed in kiwifruit export crates stored at 10 °C-20 °C reduced weight loss by 15 % and helped preserve firmness without affecting taste, addressing moisture stress linked to warming transit conditions (42). Similarly, Aloe-infused films used in strawberry clamshells cut microbial proliferation by half and delayed fungal colonization, even during transit temperature spikes up to 25 °C, simulating the unplanned thermal surges that occur during transport under rising ambient temperatures (43). These findings highlight Aloe's potential to enhance produce resilience across diverse supply chain environments.

Finally, *A. vera* gel is being applied to reduce chemical residues and enhance consumer safety, especially under environmental stress conditions. In olive curing environments exceeding 30 °C and 70 % relative humidity, pre-curing treatments with *A. vera* gel reduced sorbic acid residues by 40 %, providing a sustainable sanitation approach in climates where higher curing temperatures accelerate chemical breakdown and residue risk (52). Similarly, in mushroom packaging environments (18 °C -25 °C), Aloe protocols enabled a 70 % reduction in chlorine use while maintaining microbial safety standards, an important adaptation for regions where climate-driven heat and moisture increase pathogen loads, necessitating safer alternatives to synthetic sanitizers (53).

Fungal disease management

The rising incidence of fungal diseases in horticultural crops has been closely linked to ongoing climate shifts, particularly increases in temperature, irregular rainfall and prolonged humidity conditions that create favourable environments for pathogen proliferation. In response to the limitations of synthetic fungicides, both in terms of environmental safety and declining efficacy due to resistant strains, *A. vera* gel has emerged as a promising natural alternative for pre-harvest disease control in fresh produce (54).

Foliar applications of *A. vera* gel have shown significant efficacy in reducing fungal disease incidence in commercial fruit crops. In olive orchards, repeated applications of Aloe-based formulations during early infection stages of anthracnose (*Colletotrichum* spp.) successfully suppressed disease progression and prevented rot development, surpassing copper-based treatments in both effectiveness and crop safety (36). These formulations, derived from food-grade, non-toxic materials, exhibited no phytotoxic effects, underscoring their suitability for integration into eco-friendly management programs. Similarly, in grapevines, *A. vera* gel sprays applied at critical phenological stages, such as fruit set and bunch closure, were effective in controlling powdery mildew (*Uncinula necator*), achieving disease reductions of over 70 %, comparable to those attained with systemic fungicides like spiroxamine (27). These findings have stimulated interest in patenting Aloe-based biopesticides for viticulture, particularly under climate-challenged conditions where pathogen pressure intensifies.

Applications on produce such as strawberries and tomatoes prior to harvest have also demonstrated protective effects. The gel's bioactive constituents form a semi-permeable coating that not only inhibits fungal colonization but also enhances the fruit's intrinsic defense responses, delaying infection onset (55). *A. vera* gel's multi-targeted antifungal activity, combined with its biodegradability and compatibility with sustainable agricultural practices, positions it as a promising tool for managing pre-harvest fungal threats, especially crucial as climate change continues to reshape pathogen dynamics in horticultural systems (56). However, several challenges must be acknowledged before large-scale adoption. Variability in Aloe gel quality due to cultivar, growing conditions and extraction methods can influence consistency in efficacy. Additionally, potential sensory effects, such as alterations in fruit gloss or surface texture, as well as consumer acceptance of visible coatings, remain underexplored. From a supply chain perspective, limitations in scaling applications, particularly the labour, formulation stability and cost-effectiveness required for large-scale field deployment, represent critical hurdles. Addressing these gaps through standardization of extraction protocols, sensory evaluation studies and techno-economic assessments will be key to realizing *A. vera*'s full potential as a climate-resilient pre-harvest treatment.

Bacterial disease management

Rising global temperatures and erratic humidity levels, hallmarks of ongoing climate change, are increasingly contributing to the proliferation of bacterial pathogens during the postharvest phase of horticultural crops. These environmental shifts accelerate the growth of spoilage bacteria such as *Pseudomonas* spp., *Erwinia* spp., *Salmonella* spp. and *Listeria monocytogenes*, particularly under suboptimal storage conditions (57). This has raised significant concerns about food safety and shelf life, especially in regions where cold chain logistics are inconsistent (58). Additionally, stricter regulations and consumer demand for chemical-free produce have led to growing interest in plant-based alternatives to synthetic sanitizers and preservatives (59).

Research has shown *A. vera* gel to be highly effective in suppressing bacterial growth when applied as an edible coating or incorporated into postharvest treatments. In an experiment, it was observed that Aloe-coated guavas exhibited significantly lower bacterial spoilage and retained marketable quality for up to 10 additional days under ambient storage (60). Similarly, studies have found that *A. vera* gel significantly inhibited *L. monocytogenes* and *E. coli* populations on fresh-cut melons and pears (61). Coating papayas with Aloe-chitosan blends effectively controlled *Erwinia carotovora* infection, preserving fruit texture and reducing decay under high humidity conditions (85 %–95 % RH). These studies confirm the gel's capacity to act through both direct microbial inhibition and stimulation of host defense pathways.

Beyond coatings, *A. vera* gel has also been evaluated as a postharvest disinfectant. In citrus packing facilities, studies demonstrated that Aloe-based wash treatments significantly lowered bacterial loads in recirculated water without compromising fruit quality. Studies have reported similar findings in storage environments, where *A. vera* gel aerosols were effective in sanitizing transport containers (62). These results highlight the gel's potential as a climate-resilient, non-toxic solution for bacterial control in fresh produce supply chains.

Viral disease management

With the intensifying effects of climate change, such as elevated temperatures, increased humidity fluctuations and unpredictable precipitation patterns, horticultural crops have become increasingly susceptible to viral infections during both production and postharvest stages (63). These environmental shifts not only weaken plant defenses but also promote viral activation in storage, especially in fruits and vegetables with latent infections (64). Crops like tomato, chili, cucumber and bell pepper are particularly vulnerable, as warming climates can exacerbate the expression of viral symptoms after harvest. In response, *A. vera* gel has emerged as a natural solution due to its antiviral and immune-priming properties (65). Rich in compounds such as acemannan, anthraquinones, flavonoids and aloin, the gel acts by disrupting viral replication processes through multiple mechanisms, including inhibition of viral RNA-dependent RNA polymerase activity, suppression of coat protein synthesis and interference with viral particle assembly. Additionally, Aloe bioactives have been shown to trigger oxidative stress within infected cells, generating reactive oxygen species (ROS) that compromise viral integrity. At the host level, Aloe enhances systemic acquired resistance (SAR) pathways governed by salicylic and jasmonic acids, upregulating defense-related proteins such as pathogenesis-related (PR) proteins and β-1,3-glucanases (66).

Experimental findings further support the efficacy of *A. vera* gel against various postharvest viral diseases in key horticultural crops. In tomatoes affected by tomato spotted wilt virus (TSWV), Aloe-based coatings significantly limited symptom severity and maintained quality attributes such as firmness and lycopene concentration during cold storage. Likewise, bell peppers treated postharvest with Aloe gel exhibited reduced viral load and slower deterioration under transport stress conditions (44). In papayas exposed to papaya ringspot virus (PRSV), Aloe coatings delayed external symptom development and preserved antioxidant enzyme activity, thereby enhancing shelf life and nutritional integrity.

These findings suggest that *A. vera* gel serves not only as a physical barrier but also as a biochemical elicitor of defense, offering dual protection against virus-induced deterioration. This is especially relevant as climate shifts continue to destabilize storage environments, increasing the incidence and virulence of postharvest viral outbreaks (67). Incorporating *A. vera* gel into postharvest handling systems provides a safe, sustainable and biodegradable strategy to address the growing viral threat in climate-sensitive fruit and vegetable supply chains (68).

Foodborne pathogens associated with fresh fruits and vegetable

Foodborne diseases caused by contamination of fresh fruits and vegetables remain a major public health concern despite improvements in hygiene and postharvest practices. Pathogens such as *L. monocytogenes*, *E. coli* and *Salmonella* spp. are frequently transmitted through improper handling, mechanical injury and cross-contamination, especially in ready-to-eat and minimally processed fruits and vegetables (69). Outbreaks linked to contaminated apples, melons and leafy greens have resulted in significant health and economic consequences. Compounding the issue is the rise of antibiotic-resistant strains, which complicates conventional control strategies and increases the urgency for effective, natural alternatives (70).

A. vera gel has gained increasing attention as a plant-derived antimicrobial due to its phytochemical composition, which includes saponins, anthraquinones, acemannan and polyphenols. These compounds exhibit bactericidal and bacteriostatic effects by integrating into bacterial cell membranes, increasing permeability and causing leakage of essential ions (K^+ and Ca^{2+}) and cytoplasmic contents. Anthraquinones and polyphenols further destabilize lipid bilayers by inducing membrane lipid peroxidation, while saponins form complexes with membrane sterols, leading to pore formation and cell lysis. Additionally, Aloe bioactives interfere with microbial enzymatic systems by inhibiting ATP synthase and respiratory dehydrogenases, ultimately collapsing energy metabolism (71). Studies have demonstrated that coating fresh-cut produce such as pears, melons and apples with Aloe gel significantly reduces microbial loads and delays spoilage, effectively extending shelf life while maintaining safety and quality standards (72).

When integrated with biopolymers like chitosan, alginate and starch, *A. vera* gel's antimicrobial capacity is further enhanced. Such composite coatings form physical barriers that limit oxygen exchange, inhibit microbial invasion and retain moisture. Research on strawberries, tomatoes and mangoes has shown that these coatings significantly reduce microbial spoilage, preserve sensory characteristics and slow down respiration-related degradation under variable storage conditions (73). For instance, tomatoes treated with Aloe-chitosan coatings showed extended shelf life by up to 10 days, with minimal weight loss and higher ascorbic acid content.

Innovative packaging solutions incorporating *A. vera* gel have also shown great promise. Bioactive films and electrospun nanofibers infused with Aloe extracts were found to suppress spoilage bacteria on spinach, berries and even meat products, while preventing oxidative damage and extending freshness during storage and distribution (74). These materials not only reduce the microbial burden but also align with sustainable packaging trends by replacing synthetic preservatives and plastic-based wraps.

Apart from microbial protection, *A. vera* gel offers nutritional and functional benefits through its prebiotic compounds, particularly acemannan. This polysaccharide has been shown to selectively stimulate beneficial gut bacteria such as *Bifidobacterium* and *Lactobacillus*, promoting digestive health (75). Aloe gel's incorporation into coated produce may thus provide added value as a functional food ingredient, potentially reducing risks associated with metabolic disorders when consumed regularly alongside probiotics. This multifaceted potential positions *A. vera* gel as a practical, safe and sustainable solution for improving postharvest food safety and quality (76).

Conclusion and future prospects

The increasing vulnerability of horticultural crops to pests, pathogens and postharvest decay under climate shifts necessitates sustainable and adaptable alternatives to synthetic agrochemicals. *A. vera* gel, rich in bioactive compounds like acemannan, anthraquinones and flavonoids, has emerged as a promising solution. It offers a broad-spectrum antimicrobial effect, supports host defense activation and functions as a biodegradable coating material that helps maintain produce quality and extend shelf life. Its efficacy against fungal, bacterial and viral pathogens, along with its ability to reduce respiration rates and suppress oxidative damage, makes it particularly suitable for managing both field and postharvest challenges without contributing to environmental degradation or residue accumulation.

As climate extremes alter disease patterns, shifting infection windows, increasing postharvest latent infections and encouraging pathogen resistance, the role of *A. vera* gel in climate-resilient horticulture becomes increasingly valuable. Future research should prioritize optimizing extraction and formulation methods to enhance consistency and efficacy under diverse agroecological conditions. Investigations into Aloe gel's integration with other bioactive agents, packaging technologies and edible coatings could further improve its utility in commercial settings. Long-term safety assessments, regulatory standardization and cost-benefit analyses are also essential to facilitate its transition from experimental use to mainstream agricultural and food preservation systems. With its eco-friendly profile, consumer acceptance and multifunctional properties, *A. vera* gel presents a viable, scalable approach for enhancing plant health and postharvest sustainability in a warming world.

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Authors' contributions

LS was responsible for the preparation of the manuscript. GaD reviewed and approved the final version of the manuscript. SK, AS and CK contributed by assisting in editing, summarizing and revising the manuscript.

Compliance with ethical standards

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

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