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REVIEW ARTICLE

A Review of Post-Harvest Management Practices and Quality Optimization Strategies for Indian Gooseberry (*Phyllanthus emblica* L.)

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Abstract

Indian gooseberry (IG), also known as amla, is a nutritionally and therapeutically important fruit with extraordinary levels of vitamin C, polyphenolic content, and a wide range of therapeutic properties. Despite these benefits, commercial applications of fresh IG fruit have been limited, largely because of rapid post-harvest decay. It is estimated that one-third of the harvested crops are lost to mechanical injury, microbial decay, and physiological disorders. This review synthesizes the existing literature on integrated post-harvest management practices that can maintain the quality and prolong the marketability of IG. A structured search of Google Scholar, Semantic Scholar, ScienceDirect, Scopus, and PubMed databases was conducted to identify studies on the integrated post-harvest management of IG fruit. The retrieved evidence was synthesized and used in this review to assess practices that sustain quality and extend marketability. It discusses the effects of cultivar selection, nutrient and irrigation management, pest and disease management, and harvest maturity on post-harvest outcomes in the context of the pre-harvest to post-harvest continuum. Post-harvest handling (sorting, grading, pre-cooling, and sanitation), chemical (calcium salts and fungicides), physical (UV-C irradiation and hot-water dip), and biologically derived methods (chitosan coating and edible film) to control storability are discussed. Permeable packages, such as perforated polyethylene films, corrugated fiberboard cartons, and modified atmosphere packaging, are reviewed for their contribution to preserving IG fruit quality during shipping and storage. Storage conditions were optimized for controlled temperatures (8 °C), high relative humidity, and adequate ventilation to reduce ripening and deterioration. Integrated disease control through sanitation, temperature management, targeted use of fungicides, and emerging biological agents are key to minimizing spoilage. The potential for waste reduction and functional product development using various traditional and modern processing methods, including non-thermal preservation technologies, is explored for their ability to support waste reduction and functional product development in a global market valued at over USD 1.2 billion. The combined application of these measures is critical for extending shelf life, nutrition quality, and economic returns; enhancing the value chain of IG (both domestic and international markets); and sustaining the livelihoods of producers.

Keywords: *Phyllanthus emblica* L., Post-harvest management, Shelf-life extension, Fungal spoilage, Edible coatings, Value addition

Introduction

The Indian gooseberry (IG) fruit (*Phyllanthus emblica* L.) belongs to the *Phyllanthaceae* family and is widely cultivated across tropical and subtropical regions of the Indian subcontinent and many other countries in Asia [1,2]. It has various names but is commonly known as amla or aonla. The fruit has been well known and widely used for centuries in traditional medicine in India and many other Asian countries. IG fruit exhibits diverse therapeutic properties and nutritional profiles [3,4]. The fruit is globular, typically greenish-yellow, and characterized by a distinctly sour and astringent taste [5,6]. It is recognized as one of the richest natural sources of vitamin C, with concentrations ranging from 445 to 720 mg per 100 g of fresh weight [7-9]. In addition to ascorbic acid, IG fruit is rich in many phytochemicals, such as polyphenols (e.g., gallic acid and ellagic acid), tannins (especially emblicanin A and B), flavonoids (including quercetin and kaempferol), and other secondary metabolites [2,5,6], as well as essential minerals and trace elements such as calcium, iron, phosphorus, and chromium, which contribute to a variety of biological activities [1]. Several studies have confirmed the pharmacological properties of IG fruit, including its antioxidant, antimicrobial, anti-inflammatory, antidiabetic, hepatoprotective, gastroprotective, and anticancer activities [2,4,6,8,10]. These therapeutic properties are mainly due to the synergistic interactions between bioactive compounds, making IG a healthy food with potential applications in dietary supplements, medicines, and health drinks [2,9].

Despite its nutritional and medicinal significance, IG fruit is frequently neglected. However, despite its nutritional and medicinal importance, the commercial use of IG fruit, especially in its fresh form, is limited because it is highly perishable [11,12] and can be stored for approximately 5–6 days at ambient temperature (25-30°C), during which IG fruit deteriorates rapidly due to mechanical damage, browning, moisture loss, and microbial contamination [12-14], resulting in significant loss of quality and quantity [11,12]. Current estimates suggest that IG loss during post-harvest is approximately 30% to 40%, mainly due to the lack of proper harvesting techniques, lack of grading standards, improper packaging, and inadequate cold storage and transport infrastructure [12,15]. The browning of IG fruit is due to the enzyme polyphenol oxidase and microbial degradation, especially fungal infections, which makes storage and marketing more difficult [13,16]. Despite several recent studies exploring individual post-harvest interventions, no comprehensive review has synthesized pre-harvest, post-harvest, and processing strategies in an integrated framework specifically for IG. The present review addresses this gap by compiling and analyzing the full spectrum of IG post-harvest management, from cultivar selection and harvest maturity to treatment technologies, packaging systems, disease management, and value addition. It also incorporates recent innovations, such as edible coatings, non-thermal preservation technologies, and modified atmosphere packaging, highlighting their relevance in reducing losses and improving shelf life.

Therefore, there is an urgent need to develop and implement effective postharvest management strategies to reduce physiological and pathological losses, maintain nutritional quality, and expand marketability. Such strategies include optimal harvesting schedules, pre-chilling, innovative packaging, cold storage, the use of natural preservatives and coatings, and value addition through minimally processed products [11-13]. Advances in these areas may significantly increase economic returns to farmers, improve consumer availability, and support the development of health products using IG in domestic and international markets [1,4].

Pre-harvest factors influencing post-harvest quality

The post-harvest shelf-life and quality of IG fruit are mainly affected by pre-harvest assessments. Structural integrity, biochemical composition, and spoilage are mainly determined by several factors, including cultivar selection, agronomic practices, and harvest stage. Furthermore, these components affect not only the fruit storage period but also its suitability for fresh consumption and industrial processing. Typically, IG fruits are highly susceptible to post-harvest damage and spoilage; therefore, it is essential to optimize pre-harvest conditions to increase their commercial value and reduce waste. Among the pre-harvest factors, cultivar selection plays a major role in determining post-harvest outcomes of fruits. Among the IG cultivars, there are significant differences, which mainly fall into peel thickness, fruit firmness, chemical composition, and microbial resistance. In particular, cultivars such as

'NA-7', 'Krishna', and 'Sakkaiya' retain their physical and nutritional qualities better during storage. Furthermore, these cultivars show delayed softening, reduced browning, and higher ascorbic acid retention [17,18]. These cultivars are highly resistant to morphological and biochemical degradation, making them suitable for long-term storage and wider market distribution. Integrating these cultivars into commercial orchards may reduce post-harvest losses and increase economic returns of the orchards. Nutrient management, a key agronomic factor, plays an important role in determining fruit quality and structural integrity at the time of harvest. When nitrogen is applied in excess, it reduces fruit firmness and encourages excessive vegetative growth. Consequently, fruits with high water content may become more vulnerable to microbial spoilage and enzymatic degradation. In contrast, a balanced fertilization regime that includes potassium, calcium, and secondary nutrients such as boron and zinc can enhance fruit structure, improve structural integrity, and support the synthesis of biologically active compounds. Water management also plays a critical role in determining the post-harvest quality. Inconsistent or excessive irrigation during fruit development is often linked to physiological issues, such as fruit cracking, uneven ripening, and an overall decline in quality. Maintaining stable soil moisture levels through well-regulated irrigation supports consistent fruit development, enhances firmness, and promotes biochemical stability factors that are strongly associated with improved post-harvest performance [19].

Effective pest and plant disease management during cultivation plays an important role in maintaining post-harvest quality of the produce. Pre-harvest insect damage or disease outbreaks are often not detected until the deterioration accelerates during storage. The proper use of environmentally friendly pesticides not only reduces chemical residues but also increases the safety and storage potential of harvested produce [11]. Another important pre-harvest factor is the ripeness stage. IG fruits are generally harvested from the ripe green stage to the early yellow stage, which can occur as early as 120 days after fruit set, depending on the variety and environmental conditions [15]. At this stage, the fruit typically reaches the appropriate size, and the chemical composition stabilizes, allowing for a balance of acidity, firmness, and visual appeal that is suitable for processing. Slightly ripened fruit, which is beginning to turn yellow and possesses a sour-sweet flavor, is preferred because it yields more juice and has a better flavor. Harvesting at an inappropriate maturity stage may adversely affect the post-harvest quality. Underripe fruit generally has a poorer flavor, higher astringency, and is more prone to moisture loss and shrinkage than ripe fruit. In contrast, overripe fruits are vulnerable to mechanical injury, microbial spoilage, and premature aging, mainly due to increased respiration rates and tissue softening [20]. These fruits are not suitable for long-term storage and transportation, especially under ambient conditions. Therefore, harvest maturity should be linked to the intended end use, whether for fresh consumption, processing, or export, to ensure optimal post-harvest performance of the fruit. Combined with careful cultivar selection, balanced nutrient management, controlled irrigation, and effective pest and disease control, optimal harvest timing is the cornerstone of an integrated pre-harvest strategy. Together, these measures influence the storability, sensory properties, and overall marketability of IG fruits. Continued research and field-level monitoring of these factors are necessary to improve post-harvest outcomes and increase the commercial potential of IG fruits in domestic and international markets, particularly under changing agro-climatic conditions.

Among the various pre-harvest factors, cultivar selection and harvest maturity are consistently identified as the main factors in the literature, as they have the greatest impact on post-harvest outcomes, including shelf-life extension, nutrient retention, and microbial resistance [21]. Agronomic practices, such as balanced nutrient and irrigation management, play a significant supportive role in improving structural integrity and minimizing physiological disorders. Although moderately impactful, pest and disease control remains critical for limiting latent infections that often manifest during storage [4]. **Table 1** presents a comparative summary of these factors, ranked by their relative influence on post-harvest quality parameters. While much of the foundational work on IG cultivation and post-harvest physiology has been conducted in India, similar trends have been reported in other countries. For example, studies from Southeast and South Asia have validated the role of cultivar-dependent storability and nutritional profiles [6,22,23]. In particular, Halim *et al.*

[24] demonstrated the retention of polyphenols and antimutagenic properties in *Phyllanthus emblica* L. grown in Indonesia, which is consistent with findings from Indian cultivars. These parallels suggest the potential for the wider application of optimized pre-harvest practices in diverse agroecological settings.

Table 1 Pre-harvest factors and their influence on post-harvest quality of IG fruit.

Pre-harvest factors	Level of impact	Mechanisms affecting post-harvest quality	Example recommendations	Reference
Cultivar selection	Very high	Determines fruit firmness, peel thickness, resistance to browning and microbial spoilage; affects shelf-life and biochemical stability.	Use of 'NA-7', 'Krishna', and 'Sakkaiya' cultivars, which show delayed softening and high ascorbic acid retention.	[17,18]
Harvest maturity	Very high	Influences respiration rate, browning, spoilage risk, juice yield, and marketability.	Harvest at mature green to light yellow stage, ~120 days after fruit set.	[20]
Nutrient management	High	Affects firmness, cell wall strength, sugar-acid balance, and microbial resistance.	Balanced NPK with calcium, boron, and zinc; avoid excessive nitrogen.	[19]
Irrigation practices	High	Controls fruit cracking, internal browning, and uneven ripening.	Maintain consistent soil moisture, especially during fruit development.	[19]
Pest and disease control	Moderate	Prevents latent infections that accelerate decay during storage.	Use of integrated pest management (IPM), targeted biopesticides, and field sanitation.	[11]

Harvesting techniques and best practices

The harvesting process plays an important role in maintaining the integrity and quality of IG after harvesting. In general, IG fruit is highly susceptible to mechanical injury and microbial contamination. Poor harvesting processes and techniques can damage the IG surface and cells and increase exposure to spoilage microorganisms, thus leading to a lower shelf life. Therefore, special attention is always required, especially to the cultivation methods and processes, which will positively maintain the integrity and quality of IG fruit. Manual harvesting is the primary method of choice over mechanical harvesting because of the relatively thin rind of IG fruit and dense but fragile, blemished, and scratched tissue. IG fruit handlers should be careful during the picking, sorting, and harvesting of the fruit to avoid mechanical stress. Rough handling or accidental dropping of IG fruit can cause internal lesions, leading to discoloration, fading, and microbial spoilage. Appropriate harvesting tools, such as scissors and harvesting shears, can help harvest IG with clean cuts, leaving a short stem or stalking it on the IG fruit, and reducing the risk of peeling or stem damage. Cutting or twisting should be avoided, as it can cause stem damage, adversely affect the protective layer of IG against pathogens, and release latex on the surface, further accelerating spoilage [25]. Harvesting should be performed under dry conditions. Harvesting fruit during or immediately after rainfall greatly increases the risk of fungal contamination, as high surface moisture creates an environment conducive to spore germination and infection [11]. Wet conditions also impede visibility and handling efficiency, potentially increasing the incidence of physical damage and infestations. Generally, the early morning hours, when ambient temperatures are lower and fruit flesh is crisp, are considered the most suitable time for harvesting to minimize heat stress and maintain fruit freshness [19]. Baskets and containers used for collecting harvested IG fruit should be carefully selected, as they may induce physical injury during transport from the field to the packing or processing area. Plastic crates with smooth inner surfaces are highly suitable for IG, as they minimize the incidence of abrasions. Additionally, overfilling containers must be avoided to prevent excessive pressure and bruising, particularly during stacking and transit [19]. Adhering to best practices in harvesting not only helps maintain the physicochemical and visual quality of IG fruits but also forms a critical 1st step in an integrated post-harvest management strategy. When combined with optimal pre-harvest conditions and immediate post-harvest interventions, improved harvesting techniques can significantly reduce losses, extend shelf life, and enhance the overall marketability of the fruit. Comparative studies suggest that mechanical harvesting systems (e.g., branch shaking) can lead to fruit damage rates in excess of 25%–30%, primarily from impact bruising and stem-end breaking [26]. In contrast, manual harvesting with scissors or shears has been reported to cause mechanical injury in less than 10% if harvesting is done under dry conditions with proper handling protocols [27]. Despite being labor-intensive and increasing harvest costs by 15%–25%, manual methods for IG production are popular because of the high market penalties associated with bruised or discolored fruit. Moreover, the cost of damaged fruit and lost market quality is often greater than the savings on labor incurred by mechanical methods. Thus, although manual harvesting has a higher cost, it provides better returns in terms of fruit quality, lower post-harvest losses, and better shelf-life with higher returns, especially for fruits for the fresh market and export.

On-farm post-harvest handling

Post-harvest handling of IG at the farm level is important for maintaining quality, ensuring safety, and extending the shelf life [20,26]. Spoilage and microbial damage can be reduced by appropriate post-harvest handling. Key steps, such as sorting, grading, pre-cooling, and sanitation, play a major role in post-harvest quality and in reducing losses [27].

Sorting and grading

Grading is a crucial post-harvest step for IG, vital for upholding the quality, safety, and market value in fresh, processed, and export supply chains. Fruits are visually assessed, and those demonstrating physical damage, pest infestation, disease manifestations, or indications of immaturity or overripeness are eliminated. Fruits with defects, particularly those with mechanical damage, serve as primary avenues for pathogens such as *Penicillium islandicum*, which causes blue rot and hastens deterioration in both fresh and processed fruit products [28]. Through grading, the removal of non-conforming items helps minimize post-harvest losses and boost product reliability [20,26]. Assessment often relies on extrinsic properties, including size, shape, firmness, surface characteristics, and skin coloration, which are vital for customer preference and uniform packaging, especially in retail and international trade [29]. Smallholder farmers continue to prefer manual grading because of its ease of use and minimal cost, whereas large commercial farms tend to use mechanized systems to enhance efficiency and consistency [30]. However, mechanization enables more precise sorting based on measurable characteristics of the fruits. In addition to visual assessment, standardized grading encompasses both the physical and chemical properties. The physicochemical assessment of IG fruits is based on size (height: 2.65–4.66 cm; diameter: 2.46–5.15 cm), weight (22.3–40.12 g), firmness, and geometric sphericity, which supports efficient handling, packaging uniformity, and overall market appeal. The surface color, as measured in the CIELAB color space (L*, a*, b*), is a significant factor, wherein high lightness (L*) and balanced hue values are indicative of freshness and ripeness. The grading decisions are further supported by chemical composition. Key indicators include moisture content, which influences shelf life, and nutritional markers such as ascorbic acid (498–585 mg/100 g) and polyphenols (24.6–31.1 mg/100 g), which are crucial for the fruit's medicinal and functional food value. These intrinsic characteristics are correlated with taste, astringency, and processability [4,21].

Pre-cooling

To delay aging and preserve quality, it is essential to quickly remove the heat of IG from the field after harvest. As a climacteric and tropical fruit, IG has high respiratory activity and is susceptible to rapid spoilage if not cooled immediately [31]. IG fruit temperature can be rapidly lowered using pre-cooling methods. Water cooling (immersion or spraying chilled water) is effective but must be handled carefully to avoid microbial contamination and excessive retention of water. For uniform non-contact cooling, especially in large-scale operations, forced air cooling through vents is optimal [32]. Although the application of top or liquid icing is an infrequent practice in the transportation of IG fruit, it may be employed in emergency situations. However, this method poses potential risks, including mechanical damage and chilling injury. Zero Energy Cooling Chambers (ZECC), a cost-effective alternative, have been found to be effective in extending the shelf life of IG and reducing spoilage and respiration rates in semi-arid regions when used in combination with treatments such as calcium chloride dips [31]. In both cases, rapid pre-cooling is required to control respiration and induce slow metabolic activity, consequently extending the shelf-life of IG.

Cleaning and sanitation

Traditionally, efficient cleaning methods and sanitation are key practices for minimizing microbial load and preserving post-harvest hygiene in IG fruit. Generally, IG fruits are often contaminated with soil, dust, and microbial residues from the field, which must be removed before storage or processing [20,26]. The IG fruits should be rinsed with potable water before sanitization with 50 - 200 ppm chlorine (pH 5.0 - 7.0). Brief exposure (2–10 s) to the sanitizer significantly lowered the microbial counts. Residue-free microbial control is achievable with alternative disinfectants, such as ozonated water and diluted hydrogen peroxide (0.5%–1%), making them increasingly popular for eco-conscious practices [26]. To avoid fungal growth on IG fruits, especially given that moisture hastens spoilage, ensure that they are completely dried with forced air or absorbent cloths after washing [30]. Proper farm-level handling, including sorting, grading, precooling, cleaning, and sanitization, enhances fruit quality, reduces losses, and increases market value.

Post-harvest treatments for shelf-life extension

Post-harvest treatments are essential to prolong the useful life, improve microbial safety, and promote the marketing of IG fruits. Chemical immersion, thermal treatments, and edible coatings with functional ingredients can delay maturation, decrease degradation, and inhibit microbial growth during storage and distribution [20,26]. The perishable quality of IG fruits and the growing demand from consumers for safe and minimally processed foods have promoted the development of post-harvest technologies to minimize deterioration and preserve nutritional quality [33].

Chemical treatments

The use of calcium salts, especially calcium chloride and calcium nitrate, is one of the most widely accepted chemical treatments for IG fruits. IG fruits dipped in 1–2 %(w/v) calcium chloride solution effectively strengthened the cellular structure by cross-linking the pectin molecules, which helped maintain fruit firmness, reduced physiological weight loss, and delayed senescence. Furthermore, the use of calcium can prevent respiration and ethylene production in climacteric and tropical fruits [33]. Wax coatings are also important for extending the shelf life of IG fruits. Fruits coated with ~6% Waxol develop a semi-permeable film, minimizing moisture loss and gas exchange. In IG fruits, wax coatings help to slow down gas exchange. This can protect nutrients and keep the fruit looking fresh. Since lower respiration rates are linked to better shelf life, this can also make the fruit more appealing when sold. In many cases, growers pair wax with other treatments, such as fungicides or growth regulators, to boost results. Fungal infections after harvest, especially from *Aspergillus niger*, *Penicillium*, or *Colletotrichum*, remain a major issue. To deal with them, fungicides are often used. Chemicals such as Carbendazim or Mancozeb have been shown to stop spores from germinating and spreading disease [26]. With rising regulatory constraints and increasing consumer concerns over chemical safety, there is growing interest in using biocontrol agents and natural antimicrobials. However, adoption is still slow, mainly because of limited supply, high costs, and formulation issues [20,26]. Plant growth regulators (PGRs), such as gibberellic acid (GA_3) and kinetin, are used to enhance the ripening process and its associated biochemical activities. GA_3 application inhibits the senescence process by controlling the biosynthesis of ethylene and maintaining cell membrane integrity. The application of kinetin concurrently protects chlorophyll and ascorbic acid, thereby maintaining the nutritional and visual appeal of fruits during storage [33,34]. The use of acidulants, including citric and ascorbic acids, is especially pertinent in minimally processed or fresh-cut products from the IG fruit category. These compounds inhibit enzymatic browning by reducing the pH and deactivating polyphenol oxidase, the enzyme that catalyzes browning reactions following tissue damage. Furthermore, their use helps maintain visual and textural quality, particularly when IG fruits are processed into pulp, juice, or ready-to-eat segments [20,26].

Physical treatments

Physical treatments are rapidly gaining interest over chemical treatments in preserving IG fruits because of their residual- and chemical-free attributes. Hot water treatment (HWT) is a proven method that effectively retards microbial growth in fruits and preserves fruit quality, thus prolonging shelf life. The HWT method involves immersion of fruit in hot water that has been set between 50 and 60 °C for 1 - 2 min. Mandliya *et al.* [32] reported that HWT at 80 °C for 5 min had significantly retained the ascorbic acid and phenolic content in the IG fruits. Furthermore, ultraviolet-C (UV-C) radiation is a promising approach. Short exposure to UV-C (254 nm for 10–15 min) can reduce surface germs and increase antioxidant defenses in tropical fruits [28]. Osmotic dehydration, a semi-processing method, is used with a 2-stage process in Ig protection: dipping into hypertonic sucrose or salt solutions (35°–50° Brix), followed by hot air or vacuum drying. This reduces water activity, limits microbial growth, and helps protect flavor and nutrients. Govindarajan *et al.* [35] reported that Osmo-dehydrated IG fruit slices had demonstrated enhanced shelf-life stability and biochemical retention. High-voltage electric field (HEF) treatment is still under exploration, and no validated data are available for IG fruits. However, HEF tested on other similar types of produce has shown promise in controlling membrane permeability and microbial growth [36].

Edible coatings

Edible coatings are environmentally friendly options that help extend the shelf life of IG fruits. Generally, edible coatings are formulated from natural biopolymers, including chitosan, guar gum, xanthan gum, beeswax, and several proteins. Edible coatings often require plasticization with glycerol to enhance film formation and flexibility. When applied to food surfaces, edible coatings act as semi-permeable membranes, effectively controlling gas transmission, transpiration rate, and respiration-driven senescence processes. Among the various edible coatings, chitosan and beeswax coatings on fruits play a significant role and exhibit excellent barrier properties against moisture and pathogens. Generally, chitosan is an antifungal agent when coated with fruits. It forms a cohesive film that impedes microbial growth and causes oxidative deterioration. In contrast, beeswax exhibits good hydrophobicity and enhances the resistance of fruit against moisture loss. Liu *et al*. [37] reported that composite film made of chitosan, pullulan and zein with Artemisia argyi essential oil and coated with IG fruits had significantly reduced the quality deterioration during storage by providing effective barriers against oxidative stress and microbial growth. Furthermore, their study also suggested that the application of edible coating helped retain moisture, controlled the respiration rate, and altered the internal fruit atmosphere by enhancing CO_2 accumulation. This reduces oxidative stress and enzymatic degradation, thereby preserving the firmness, color, and nutrients. When infused with natural antimicrobials, such as essential oils, they also inhibit microbial growth and reduce susceptibility to mechanical damage. Singh *et al*. [38] reported that encapsulation of EO in a chitosan based edible coating had boost up the antifungal protection and shelf stability of fruits while maintaining consumer acceptability. Due to their high moisture content and susceptibility to microbial and oxidative damage, edible coatings are particularly beneficial for industrially processed fruit. To promote the commercialization of fresh and minimally processed IG products, further research on innovative, biodegradable, and cost-effective coating technologies is necessary. While edible coatings have demonstrated the advantages of extended shelf life and quality retention, their adoption of edible coatings in small-scale or rural post-harvest systems is impeded by substantial economic and logistic barriers. Biopolymer-based coatings, such as chitosan, pullulan, and zein, are costly to source and process, especially in places without infrastructure for manufacturing or extracting such polymers [39]. Moreover, common application methods, such as dipping or spraying, require controlled environments and equipment, which are often not accessible or affordable for smallholder producers [40]. In many instances, edible coatings are limited to industrial applications because access to commercial biofilms and packaging systems is not affordable by local vendors [39]. This makes it imperative to develop low-cost, local alternatives and simplified application methods that can be realistically adopted by decentralized producers. **Table 2** provides a comprehensive overview of the major post-harvest treatments for IG fruit.

Table 2 Comparative overview of major post-harvest treatments for IG fruit

Type	Treatments	Mode of action	Advantages	Limitations	Reference
Chemical	1% - 2% Calcium chloride dip	Strengthens cell walls, delays senescence	Maintains firmness, reduces weight loss	Residue concerns, may alter taste	[33]
Chemical	Potassium metabisulphite (KMS) blanching	Preservative; inhibits microbial growth	Reduces microbial spoilage, maintains quality	Possible sulfite sensitivity	[41]
Botanical Fungicide	Natural plant extract	Antifungal; inhibits spore germination	Controls *Penicillium*, *C*	Regulatory restrictions, consumer concerns	[42]
Physical	Hot water treatment, microwave blanching	Reduces microbial load; enzyme inhibition	Retains antioxidants, delays browning	Risk of over-processing	[32]
Physical	Zero energy cool chamber	Maintains cool storage, reduces respiration	Extends shelf life, preserves quality	Requires specific infrastructure	[31]
Biological	Chitosan edible coating + essential oils	Forms semi-permeable barrier; antifungal	Inhibits microbial growth, reduces weight loss	Cost, shelf-life of coating	[43]

Recent studies have shown that post-harvest combined treatments might be beneficial owing to their synergistic effects in extending the shelf life and improving the quality of IG fruits. For instance, hot water treatment followed by chitosan coating can improve microbial control while decreasing water loss because of the double action of microbial inactivation and barrier formation [32,37]. Similarly, combining UV-C irradiation with edible coatings containing essential oils has been found to enhance the antifungal properties and maintain the physicochemical properties of other tropical fruits [38]. However, there is not much data specific to IG. Further studies are needed to optimize the sequence, dosage, and compatibility of combined treatments for cost-effective and scalable solutions for commercial applications.

Packaging systems for post-harvest preservation

Packaging is crucial for the post-harvest management of IG fruits, as it protects against physical injury and creates a microenvironment that extends shelf life. Despite the chemical and structural differences among packaging materials, it is difficult to mitigate moisture loss, suppress respiration, control ripening, and prevent microbial contamination, particularly during handling, storage, and distribution, without effective strategies. IG fruits require careful packaging due to their climacteric nature and high susceptibility to dehydration, fungal infection, and bruising, especially in supply chains involving extended storage or export. Polyethylene (PE) films are commonly used because of their semi-permeable nature, which controls gas movement and helps reduce water loss without inducing anaerobic conditions. Perforated PE bags are especially useful for fruits sensitive to CO_2 buildup; the size and number of perforations influence the internal air composition, thereby affecting the respiration rate and shelf life. Singh *et al.* [44] reported that low-density polyethylene (LDPE) bags significantly reduced weight loss and decay in IG fruits over a 12-day storage period at room temperature, while preserving ascorbic acid and titratable acidity. Similar results have been observed in tropical fruits such as pomegranate and purple passion fruit, where perforated packaging maintained relative humidity close to 95%, limiting shriveling [45,46]. However, excess humidity may lead to condensation, encouraging fungal proliferation, particularly by *Aspergillus* and *Penicillium* species. Corrugated fiberboard (CFB) boxes are widely used for bulk packaging because of their strength, stackability, and moderate ventilation. When combined with polyethylene liners, they can reduce moisture loss by 20–30% during transport. Their porous structure dissipates heat and moderates gas exchange, although there are limited direct data on the use of CFB for IG fruits. Thakur *et al*. [47] studied a processed IG-based squash product and showed that appropriate primary packaging preserves color, acidity, and microbial stability. However, quality gains can be undermined during distribution if secondary packaging fails, as untreated CFD readily absorbs moisture and may lose its structural integrity in high humidity. Hydrophobic or wax coatings mitigate this risk and prevent box collapse. Wooden crates are also used for IG packaging, especially in rural and bulk-handling contexts, because of their mechanical durability and reusability. When paired with polyethylene liners, wooden crates help stabilize the relative humidity, slow transpiration, and maintain fruit freshness and weight. Their usefulness is evident in long-distance transport without the need for refrigeration. Research on aonla shows that hardwood crates combined with liners help preserve physicochemical properties during storage [15,48], supporting their relevance for IG distribution in arid and semi-arid regions. However, these crates are heavy, increasing transport costs, and may splinter, posing risks to the fruits and handlers. Environmental concerns, such as deforestation and the poor biodegradability of plastic liners, also limit their long-term sustainability and export suitability. Modified atmosphere packaging (MAP) is a more advanced option, wherein internal gas levels are adjusted, typically reducing oxygen to 3–5% and increasing carbon dioxide to 10–15%, to suppress respiration, delay ripening, and limit enzymatic activity. The physiological responses of IG fruits under MAP include slower chlorophyll degradation, better titratable acidity retention, and reduced electrolyte leakage. Killadi *et al.* [49] found that combining MAP with calcium treatments significantly enhanced visual quality and shelf life under refrigeration, while Singh *et al*. [44] reported that LDPE-based MAP reduced weight loss and preserved ascorbic acid over 12 days. Additional studies have confirmed that MAP storage at 5 °C helps retain polyphenols and minimize browning compared to ambient storage [16,50]. The effectiveness of MAP depends on matching the packaging film permeability with the respiration rate of the fruit; poor alignment may cause excessive CO_2 buildup, oxygen depletion, off-flavors, or anaerobic stress. Furthermore, MAP systems require reliable cold-chain infrastructure and have relatively high costs, limiting their adoption in decentralized or smallholder supply chains.

Contemporary post-harvest management increasingly promotes the integration of packaging systems with additional preservation technologies to enhance the effectiveness of storage (**Table 3**). This approach merges the physical protection offered by packaging with the biochemical and physiological benefits conferred by treatments, such as edible coatings or modified atmospheres. Although studies directly targeting IG remain limited, research on closely related tropical fruits suggests that such combinations are both feasible and potentially effective in treating diabetes. For example, Kusum *et al.* [51] reported that aloe vera-based edible coatings, when used in conjunction with modified atmosphere packaging, significantly improved the shelf life and reduced decay incidence in *Ziziphus mauritiana* (ber), some fruit with post-harvest characteristics analogous to those of IG fruits. Edible coatings applied before packaging function as primary barriers to limit moisture loss and microbial ingress. The subsequent application of external packaging provides mechanical protection and facilitates environmental regulation, thereby forming a multilayered preservation system. Studies involving tropical and subtropical fruits have shown that this dual strategy can reduce physiological weight loss, delay ripening, and improve the retention of ascorbic acid and other nutritional constituents [52,53]. However, the translation of these results into commercial practice remains constrained by inconsistencies in coating performance, possible interactions with packaging films, and the absence of standardized formulations and application procedures for these coatings. The successful implementation of integrated packaging technologies requires a systematic understanding of the interactions between coating composition, film permeability, fruit respiration dynamics, storage temperature, and distribution logistics of the fruit. Future innovations in the form of biodegradable polymer films, active packaging technologies such as ethylene scavengers, and cost-effective modified atmosphere solutions may provide scalable, environmentally sustainable methods for improving the post-harvest quality and marketability of IG fruits, particularly in minimally processed and fresh-fruit contexts.

Table 3 Packaging methods, storage conditions, and quality attributes of IG fruits.

Packaging type	Storage conditions	Shelf-life extension	Preservation of quality attributes	Reference
Perforated PE bags (LDPE)	25 - 30 °C	Up to 12 days	Ascorbic acid, firmness, reduced weight loss	[44]
Corrugated fiberboard (CFB) boxes with liners	25 - 30 °C	Moderate (5 - 10 days)	Reduced bruising, moderate moisture retention	[15]
Wooden crates with polythene liners	25 - 30 °C	Up to 15 days	Moisture, firmness preserved; reduced physical damage	[48]
Modified Atmosphere Packaging (MAP)	5 °C	2 - 3 weeks	Browning prevention, phenolics, acidity retention	[49,50]

Optimizing storage conditions for quality maintenance

Proper storage conditions are critical for extending the post-harvest life of IG fruits and preserving their nutritional, physicochemical, and sensory properties. As a climacteric fruit, IG is highly sensitive to storage conditions, including temperature, relative humidity, and ambient gas composition. Its high moisture content and thin pericarp make it highly susceptible to desiccation, oxidative browning, and microbial deterioration when stored under unfavorable conditions. Temperature management is a key component of post-harvest management. Refrigerated storage at 4–5 °C was found to minimize enzymatic browning and phenolic degradation in IG juice, while there was an improved retention of bioactive compounds such as gallic acid and ellagic acid [16,50]. These observations indicate that low temperatures inhibit polyphenol oxidase activity and senescence-related processes. In parallel, it is advisable to maintain the relative humidity between 90% and 95% to avoid water loss and loss of turgor. However, high humidity levels must be carefully managed to prevent condensation, which can be conducive to fungal colonization. Using a controlled low-temperature storage process, experimental studies have shown that IG can maintain commercial acceptability for 21 days. Nonetheless, if proper packaging and sanitation are not provided, visible deterioration frequently starts within the first week of storage. When stored at room temperature (25–30 °C), the shelf life is drastically shortened to approximately 5–6 d, which is attributed to the accelerated respiration and growth of microorganisms [54]. In addition to environmental control, cultivar-specific responses play a major role in determining storage performance. Some cultivars, such as 'Krishna' and 'NA-7,' have been found to show better cold-storage behavior with higher firmness and lower browning indices under refrigeration [17,18]. They have a heavier peel and are also thought to have greater resistance to chilling stress and enzymatic degradation due to their higher antioxidant content. In addition, storage performance can be further improved by pre-storage interventions, such as calcium chloride dips or by using MAP. Killadi *et al*. [49] reported that MAP, especially in combination with a Ca-based coating, significantly delayed softening, weight loss, and rot symptoms during 21 days of cold storage. However, the success of such integrated approaches strongly relies on a stable cold chain, which is often absent in smallholder or rural supply systems. Ethylene control is another important but poorly investigated aspect of IG storage.

Ethylene control is another important but unexamined aspect of IG storage. Despite being classified as a climacteric fruit, IG seems to act more like an intermediate climacteric fruit with a relatively low sensitivity to exogenous ethylene compared to highly sensitive climacteric fruits such as bananas or mangoes. However, anecdotal evidence and preliminary observations indicate that passive exposure to ethylene, especially in high humidity or mixed storage with ethylene-producing fruit, may still contribute to softening, loss of firmness, and browning. Critically, there are no peer-reviewed studies on the ethylene sensitivity of IG or testing of ethylene-suppression technologies such as 1-methylcyclopropene (1-MCP). This presents a large knowledge gap in post-harvest handling, especially given that the incorporation of ethylene control into storage systems could improve shelf-life and quality maintenance. Given the increasing commercial importance of IG and its climacteric classification, there is a need to characterize the ethylene response profile of IG, establish threshold concentrations for quality degradation, and evaluate the efficacy of ethylene blocking or scavenging treatments in selected cultivars and storage systems. Until such data are available, only passive management strategies, including ventilation, temperature, and segregation from ethylene-emitting fruits, can be recommended with any confidence for mixed storage environments.

Ventilation plays a critical role in maintaining the quality of fruits. Good ventilation minimizes the accumulation of metabolic heat and ethylene, prevents localized increases in humidity, and reduces the potential for microbial infection. Forced air cooling systems have been found to be very effective in controlling surface condensation and the distribution of temperature. Under stagnant air conditions, particularly when combined with a high humidity level, Jat *et al*. [55] reported an increase in fungal infections, such as *Aspergillus* and blue mold rot. Although there are no formal ventilation guidelines. For IG, the integration of airflow management with temperature and humidity control is generally perceived as critical for maintaining post-harvest quality. Although different technological options exist, logistical and infrastructural constraints are important issues in many IG-producing regions. Small-scale producers have limited access to cold storage facilities, insulated transport, and packaging materials for humidity control. In addition, even high-quality fruit harvested at the best possible stage will not reach far-away markets without significant post-harvest losses. Future research should include the development of low-cost storage technologies suited to the local climate, cultivar, and market needs, as well as the assessment of technologies such as MAP, 1-MCP, and humidity-controlled transport containers in IG supply chains.

Post-harvest diseases and their management

Post-harvest diseases are one of the principal limitations to the storage stability and commercial viability of IG fruits. Post-harvest diseases in IG fruits are predominantly induced by fungal growth, leading to both qualitative deterioration and quantitative losses, particularly when fruits are stored under warm temperatures, high humidity, and inadequate ventilation. Among the documented pathogens, blue mold rot caused by *Penicillium islandicum* is particularly concerning. Saini *et al*. [30] reported an incidence rate of up to 7.5% in terminal markets across India after 10 days of ambient storage. These infections commonly arise from micro-wounds acquired during harvesting or handling and tend to proliferate under suboptimal post-harvest conditions. The management of post-harvest fungal diseases requires a holistic strategy that integrates pre-harvest field sanitation, hygienic harvesting practices, and carefully controlled storage environments. In addition to conventional practices, recent interest has focused on the use of biological control agents and natural antimicrobials, including those derived from IG fruits. Begum *et al*. [56] reviewed existing studies demonstrating that *Phyllanthus emblica* possesses antifungal activity against a variety of phytopathogens including *Colletotrichum gloeosporiatides*, *Fusarium solani*, *Aspergillus niger*, *Candida albicans* and *Macropomina phaseolina*, highlighting the potential of the fruit in developing bio-based protection technologies for post-harvest disease management. In general, complex interactions between host physiology, microbial ecology, and environmental factors lead to the development of post-harvest diseases in IG fruits. **Figure 1** summarizes the key contributors to disease onset and the integrated management strategies available to mitigate spoilage in IG fruits.

Major fungal diseases

Multiple fungal pathogens have been identified as key contributors to the post-harvest deterioration of IG fruit. Among these, blue mold rot remains the most frequently reported, with causative agents including *Penicillium islandicum*, *P. oxalicum*, and *P. digitatum* (**Table 4**). The disease typically initiates with localized water-soaked lesions that progress into dense bluish-green spore masses, often accompanied by a characteristic musty odor. These pathogens enter the fruit primarily through surface injuries or microcracks that occur during harvesting, sorting, or transportation [30]. Another major post-harvest disease is anthracnose, which is caused by *Colletotrichum gloeosporio*. This infection initially appears as small, sunken, dark lesions that gradually enlarge and coalesce, leading to tissue necrosis, softening, and a reduced shelf life. The pathogen often remains quiescent during the early stages of fruit development and becomes active under warm and humid storage conditions after harvest [57,58]. Fruit rot is another significant concern, caused by a diverse group of fungal pathogens, including *Phomopsis phyllanthus*, *Aspergillus niger*, *Nigrospora sphaerica*, and *Rhizopus stolonifer*. Among these, *Rhizopus stolonifer* is particularly aggressive, rapidly invading the fruit under ambient storage conditions and causing tissue breakdown, liquefaction, and the eventual collapse of the fruit structure. Saini *et al*. [58] reported that such infections are especially problematic in storage systems lacking refrigeration or adequate airflow. These disease profiles emphasize the importance of preventive handling measures, proper sanitation during post-harvest operations, and the implementation of optimized storage protocols to limit fungal proliferation and extend the marketable shelf life.

Table 4 Common post-harvest diseases of IG fruits and their management strategies.

Disease	Microorganisms	Symptoms	Management approaches	Reference
Blue mold rot	*Penicillium islandicum*	Soft rot, bluish-green spores	Sanitation, fungicides (carbendazim), low-temp storage	[30]
Anthracnose	*Colletotrichum gloeosporioides*	Dark sunken lesions, tissue necrosis	Field sanitation, hot water, UV-C, biological controls	[11]
Fruit rot	*Aspergillus niger*, *Rhizopus stolonifer*	Soft breakdown, black or mushy spots	Calcium dips, ventilation, refrigeration	[57,58]
General fungal spoilage	Various	Browning, softening, off-odor	Edible coatings, modified atmosphere packaging	[26]

Sanitation and integrated disease management

Sanitation is the foundational element of post-harvest disease control in IG fruits. The disinfection of harvesting tools, collection containers, packing surfaces, and storage facilities plays a critical role in minimizing the initial inoculum levels. The use of clean packaging materials and adherence to established good agricultural practices (GAP) and good handling practices (GHP) further reduce the risk of pathogen spread during post-harvest handling, storage and transport. Temperature management, particularly through pre-cooling and refrigerated storage between 0 and 2 °C, is essential for slowing fungal metabolism and inhibiting the development of lesions. However, care must be taken to manage the relative humidity to prevent condensation, which could facilitate fungal proliferation. Chemical fungicides, such as carbendazim and mancozeb, have been reported to be effective against key post-harvest pathogens, including *Penicillium islandicum* and *Colletotrichum gloeosporioides* [11]. Despite their efficacy, concerns regarding chemical residues and evolving regulatory restrictions necessitate cautious and targeted applications. Residue-free physical treatments are gaining prominence as sustainable alternatives to chemical treatments. Hot water treatment (HWT) and ultraviolet-C (UV-C) irradiation have demonstrated potential for reducing fungal load and delaying decay in IG fruits (**Table 5**). Sharma and Srivastava [59] reported that HWT and UV-C treatments not only suppressed microbial proliferation but also enhanced the fruit's endogenous defense systems by stimulating enzymatic activity. Biological control strategies also offer promising solutions, utilizing antagonistic microorganisms such as *Trichoderma* species and *Bacillus subtilis*, as well as plant-derived antifungal agents, including essential oils. Although environmentally favorable, these methods face challenges related to formulation stability, application consistency, and scalability for commercial use. In parallel, calcium-based treatments have shown potential to improve post-harvest disease resistance by reinforcing cell wall structure and maintaining fruit firmness [20,26]. Overall, an integrated disease management strategy that combines sanitation, temperature and humidity control, selective fungicide application, physical treatment, and biological control agents is considered the most comprehensive approach for mitigating post-harvest losses in IG fruits.

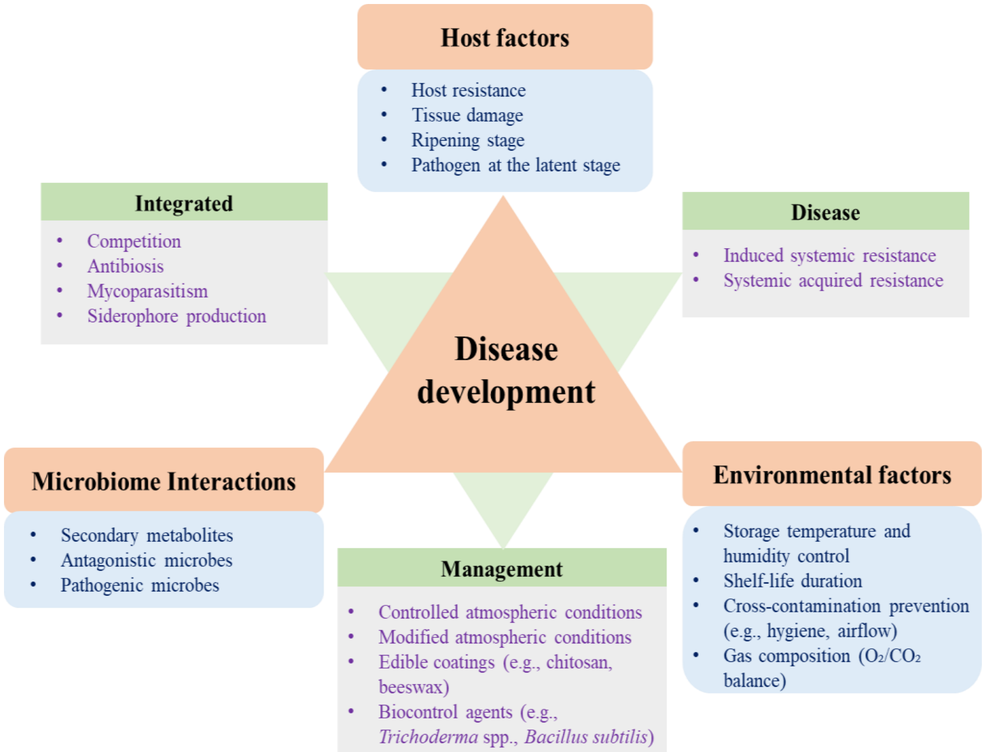

Figure 1 Conceptual framework illustrating the development of post-harvest diseases in IG fruits.

Table 5 Comparison of post-harvest treatments and their effects on IG.

Treatments	Condition	Effects	Drawbacks/Limitations	Reference
Chemical treatment	1% - 2% Calcium chloride dip	Maintains firmness, delays senescence	Residue concerns, consumer acceptance	[33]
Wax coating	6% Waxol	Reduces moisture loss, slows respiration	May affect flavor/appearance	[33]
Fungicide application	Carbendazim, mancozeb	Controls fungal spoilage	Regulatory and safety issues	[26]
Hot water treatment	80 °C for 5 min	Preserves antioxidants, reduces decay	Risk of overprocessing	[32]
Edible coatings	Chitosan, beeswax	Reduces weight loss, inhibits microbes	Varies by formulation, shelf stability	[37]
UV-C treatment	254 nm, 10 - 15 min	Reduces surface microbial load	Limited commercial validation	[59]
Osmotic dehydration	50° Brix sugar solution	Enhances shelf-life and flavor	Labor intensive, loss of volatiles	[35]

Value addition and processing technologies

Value addition and post-harvest processing of IG fruits are critical strategies for minimizing post-harvest losses, extending shelf life, and enhancing the economic viability of the fruit. Due to their high perishability and short fresh market shelf life, a significant proportion of harvested IG fruits, especially those that do not meet fresh market quality standards, are diverted to processing applications. This redirection not only reduces waste but also supports the development of functional and nutraceutical food products that meet diverse consumer and therapeutic needs (**Table 6**). Muzaffar *et al*. [26] provide a detailed overview of the post-harvest technologies utilized for transforming IG fruits into a variety of value-added forms, including juices, candies, preserves, powders, and confections. These products are known to retain a substantial portion of the fruit's inherent nutritional and medicinal properties, particularly its high vitamin C, polyphenol, and hydrolyzable tannin content, which contribute to its antioxidant and therapeutic potential. Several innovative applications have been reported in the literature. Bishnoi *et al*. [60] reported the development of herbal IG fruit ladoos fortified with *Asparagus racemosus* (Shatavari) root extract, yielding a functional snack product with elevated levels of bioactive compounds and improved nutraceutical potential. Similarly, Cheekham *et al.* [61] investigated the incorporation of IG fruits into various food matrices and observed that drying-based processing methods were effective in concentrating phytochemicals and increasing antioxidant capacity. In contrast, thermal treatments, such as boiling or pickling, were associated with significant degradation of ascorbic acid and polyphenolic content. These findings highlight the dual benefits of processing IG fruits for nutritional retention and commercial diversification. However, the wider adoption of value-added IG fruit products will depend on the standardization of processing protocols, improved consumer awareness of their health benefits, and the development of robust supply chains and market linkages. An integrated overview of the post-harvest supply chain, including the stages from harvesting to marketing, is presented in **Figure 2**. This highlights the need for coordination among producers, processors, and policymakers to unlock the full potential of processed IG fruits.

Table 6 Stage-wise post-harvest management strategies for IG.

Stages	Key methods	Functions	References
Pre-harvest	Cultivar selection (e.g., 'NA-7', Krishna), balanced fertilization, IPM	Enhance firmness, reduce decay susceptibility	[17,19]
Harvesting	Manual harvesting, dry weather timing, sanitized tools	Minimize mechanical injuries and microbial entry	[11]
Initial handling	Sorting, grading, pre-cooling, sanitation	Remove infected/damaged fruit, delay respiration	[26,27]
Post-harvest treatments	Calcium dips, wax coating, edible films, UV-C, thermal blanching	Delay senescence, reduce microbial load	[32,33]
Packaging	MAP, perforated PE bags, fiberboard boxes with liners	Reduce moisture loss, prevent bruising	[15,44]
Storage	0 - 5 °C, 90% - 95% RH, adequate ventilation, ethylene segregation	Prolong shelf life preserve phytochemicals	[16,59]
Value addition	Juices, powders, Osmo-dehydrated slices, herbal confections	Utilize surplus, expand market access	[60,62]

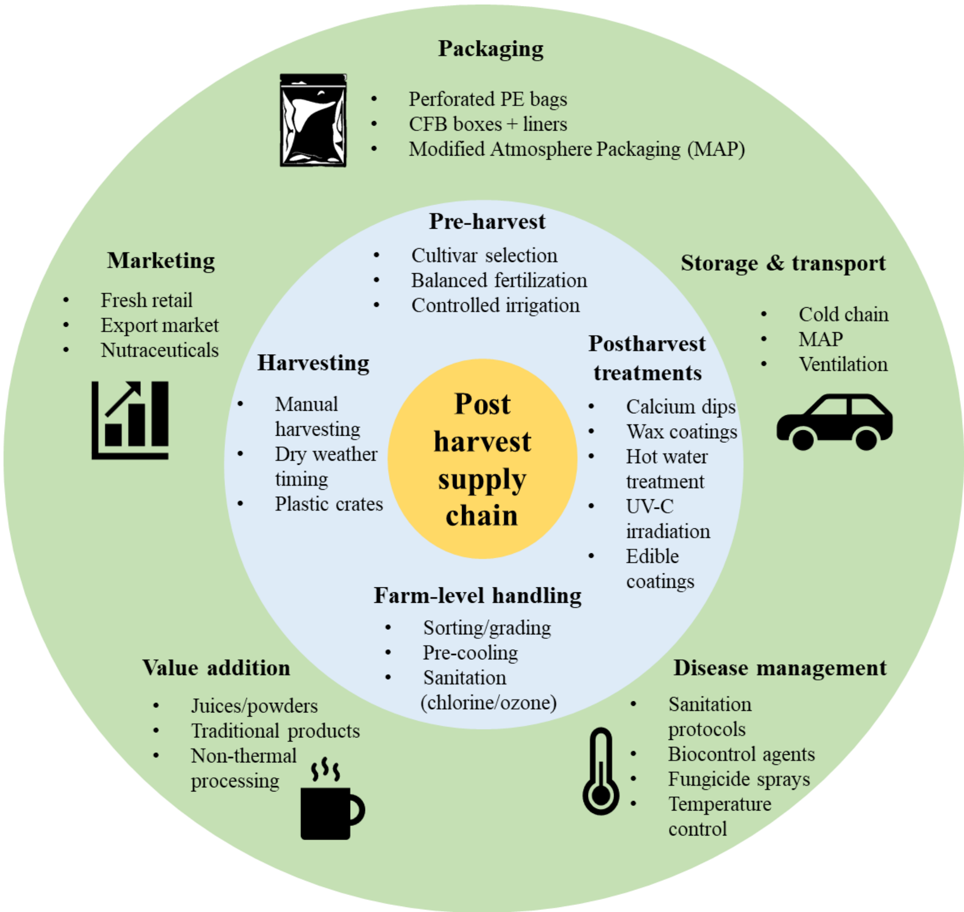

Figure 2 Overview of the post-harvest supply chain components for IG fruits.

Minimizing post-harvest losses through processing

Processing provides a practical and efficient outlet for IG fruits that are unsuitable for the fresh market due to minor blemishes, over-ripening, or handling-induced stress. Despite their reduced aesthetic appeal, these fruits often retain their internal nutritional and phytochemical integrity, making them ideal candidates for transformation into value-added products. The redirection of cosmetically imperfect or surplus fruits into processing pipelines significantly reduces on-farm and supply chain losses while improving resource-use efficiency and enhancing farmer income. Yadav *et al.* [63] highlighted that up to 30–80% of IG fruits in North India are affected by superficial defects, such as brown spots, which diminish their marketability for fresh consumption. Although these fruits are commercially downgraded, they still possess high nutritional value and can be effectively utilized in the production of juices, powders, or preserves. The strategic processing of these fruits is a critical intervention for supporting sustainable post-harvest utilization and value recovery.

Processed products and innovative processing techniques

IG processing is central to reducing post-harvest losses and extending shelf life and market availability. Traditionally, IG is converted into juices, syrups, and preserved fruits, which are appreciated for their high antioxidant activity and vitamin C. These products, especially in water formats, are typically stabilized through thermal pasteurization or chemical preservatives, which suppress microbes but degrade heat-sensitive nutrients such as ascorbic acid and polyphenols. Declines in antioxidant potential have been reported after thermal stabilization and pickling [61]. Evidence in the literature confirms that processing can decrease losses while expanding market availability. However, the constant trade-off between quality and safety with heat-based methods has motivated the search for alternatives. Drying methods such as hot air, vacuum, and solar drying increase shelf life and often concentrate bioactive compounds, but can detrimentally affect texture and flavor. Assisted approaches are being developed to address these disadvantages. High-pressure processing (HPP) is an inactivation method that involves minimal heat treatment; thermally assisted HPP of IG juice has maintained ascorbic acid, color, and antioxidant capacity more effectively than conventional pasteurization [64]. Ultrasound-assisted techniques can improve the efficiency of drying and the extraction of bioactives. The combination of ultrasound with medium-wave infrared during drying improved nutrient retention compared to conventional drying [65,66]. Ultrasound-assisted extraction combined with green solvents improved flavonoid and polyphenol yields. At the formulation stage, clarification using agents such as gelatin and bentonite enhanced the physical, microbial, and sensory qualities during refrigerated storage, offering the potential for an extended shelf life with low nutrient loss. Product diversification is also developing in parallel. IG has been added to juices, syrups, preserved fruits, candy bars, dried shreds, jams, and functional drinks such as kombucha. Formulations fortified with spices and condiments, such as turmeric, black pepper, and ginger, have demonstrated increased antioxidant capacity, combining traditional ingredient synergies with modern processing. Despite these promising signals, most nonthermal and assisted technologies are in the pilot or early commercial stages. Barriers include capital costs, scale-up engineering, process validation across variable IG cultivars and maturities, regulatory clearance, demonstration of sensory acceptance, and evidence of long-term stability under realistic distribution conditions. These constraints are especially acute for smallholders and SMEs, for whom cost-effective edible coatings and packaging solutions, reliable cold chains, and targeted training are prerequisites for adoption.

Global market and economic potential

IG is an economically significant fruit, with production concentrated in India, which accounts for more than 80% of the global output owing to the favorable agroclimatic conditions in regions such as Madhya Pradesh, Maharashtra, and Southern India [67]. The crop supports rural livelihoods and is featured in arid and semi-arid horticulture development programs. Over the past decade, exports of IG from India have grown at an estimated 10–15% per year, driven by the rising international demand for natural health supplements and nutraceuticals. The global herbal supplements market, to which IG-based products contribute, is projected to grow at a compound annual rate of approximately 6% to 8%, creating additional opportunities. Although precise export values specific to IG are limited in publicly accessible sources, broader trends in India's horticultural exports indicate a positive trajectory that benefits IG as a niche commodity [68]. Major export destinations include North America, Europe, and Southeast Asian countries such as Thailand, Malaysia, and Vietnam. These markets have an expanding demand for functional foods, herbal beverages, and antioxidant-rich nutraceuticals, where IG is typically traded as dried powders, extracts, concentrated juices, and functional ingredient formulations. Southeast Asian countries, including Thailand, are increasingly engaging in IG cultivation and product development, complementing India's export supply. Processed IG products retain high levels of antioxidant compounds and vitamin C, which are important for the efficacy of health products and enhance their commercial value. Studies have reported that functional herbal drinks containing IG maintain significant bioactive compound stability, supporting market acceptance in the health and wellness categories [69]. Overall, IG is positioned as a vital commercial crop with substantial growth potential, supported by its nutritional and ethnomedicinal attributes, robust export growth from India, and widening presence in global and regional health markets. Continued progress in value addition and quality control will be critical to further strengthening its economic impact in South Asia and Southeast Asia.

Conclusions

Post-harvest handling of IG is critical for increasing commercial sustainability and nutrition. IG fruits have been reported to have significant health benefits and economic importance but are underutilized in their fresh form due to rapid perishability, susceptibility to mechanical injury, microbial spoilage, and physiological degradation. Effective pre-harvest handling (including cultivar selection, nutrient and irrigation practices, pest and disease control, and timely harvest) conditions post-harvest handling performance. Post-harvest strategies, such as sorting, grading, precooling, and sanitation, are important for maintaining physiological freshness and microbial safety. Major techniques include the use of chemical preservatives, intermittent hot water treatment, cold storage, and biological control agents. Packaging technologies, particularly edible coatings and controlled/modified atmosphere systems, can assist in quality control during handling and distribution. Storage conditions must be well controlled; low temperature, high relative humidity, and good ventilation delay senescence and help reduce spoilage. Disease prevention includes hygiene, controlled storage, selective fungicides, and novel physical and biological treatments. In parallel, value addition through traditional and modern processing allows the use of off-grade fruit and opens the door to new market opportunities, thus, the production of value-added IG products suitable for nutritional and therapeutic applications. Recent advances in nonthermal preservation (e.g., high-pressure processing) and ultrasound-assisted drying/extraction have shown promise but have yet to be tested for IG. Accordingly, five priority research directives were identified: 1) validation of the scalability of non-thermal technologies such as UV-C, HPP, and ultrasound processing); 2) development of cost-effective and biodegradable edible coatings suitable for smallholders; 3) Characterization of IG ethylene sensitivity and ventilation needs; 4) optimization of integrative packaging systems combining mechanical protection, MAP, and active agents; and 5) detailed market studies to quantify economic impacts and provide information for policy purposes. Policy recommendations, particularly investment in cold-chain infrastructure and farmer training, are also emphasized.

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Declaration of Generative AI in Scientific Writing

The authors declare that no generative AI or AI-assisted technologies were used in the writing, editing, or preparation of this manuscript. All content was developed solely by the authors.

CRediT Author Statement

Conceptualization, **N.C and K.V**; software, **N.C., Z.B., L.L., B.P and K.V.**; validation, **N.C., Z.B., L.L., B.P and K.V.**; investigation, **N.C and K.V.**; writing - original draft preparation, **N.C and K.V.**; writing - review and editing, **N.C., Z.B., L.L., B.P and K.V.**; supervision, **K.Y. and N.C.** All authors have read and agreed to the published version of the manuscript.

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