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*Review Article*

# Post-Harvest Preservation of Okra (*Abelmoschus esculentus* L.): A Comparative Review with Emphasis on Freeze-Drying

**Muhammad Muhammad Abubakar[1,2], Nyuk Ling Chin[1]*, Yus Aniza Yusof[1], and Nor Amaiza Mohd Amin[1]**

[1]*Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia*

[2]*Department of Agricultural and Bio-Environmental Engineering Technology, Ramat Polytechnic Maiduguri, 600251 Borno State, Nigeria*

## ABSTRACT

Okra is a nutritious but highly perishable vegetable that requires appropriate preservation strategies to reduce post-harvest quality losses. This review examines the main physical, chemical and processing methods used to preserve okra, with particular emphasis on freeze-drying as an alternative to conventional drying techniques. A systematic literature review was conducted using the Protocol, Search, Appraisal, Synthesis, Analysis and Report (PSALSAR) framework. Preservation methods were compared, where evidence was available, in terms of nutrient retention, texture and microstructure, rehydration and functional properties, sensory quality, and energy and cost considerations. The evidence suggests that freeze-drying can improve the retention of selected heat-sensitive compounds, preserve product structure and enhance rehydration compared with some conventional drying methods. However, its application is constrained by high energy consumption and capital costs. Cold storage, chemical treatments or conventional drying may offer greater operational simplicity and lower capital costs, although their effects on product quality depend on the treatment, storage and processing conditions and intended use. A comparative summary of the methods is presented, together with research gaps and future priorities. The review highlights the need for standardised reporting of preservation and drying parameters and for techno-economic studies to assess the feasibility of these technologies in resource-limited settings.

*Keywords:* Cold storage, freeze-drying, modified atmosphere packaging, Okra, post-harvest preservation

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*E-mail addresses*:
muhammadabubakar1336@gmail.com (Muhammad Muhammad Abubakar)
chinnl@upm.edu.my (Nyuk Ling Chin)
yus.aniza@upm.edu.my (Yus Aniza Yusof)
myza@upm.edu.my (Nor Amaiza Mohd Amin)
* Corresponding author

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## INTRODUCTION

Okra (*Abelmoschus esculentus* L.) is a member of the Malvaceae family and is widely cultivated across tropical and subtropical regions and has a significant nutritional and economic role in Africa, Asia and parts of the Middle East (Rababah et al., 2023). In Asia, okra is widely grown in India, Pakistan and Bangladesh. In these countries, the trend is to use modern agricultural technologies to reduce crop losses caused by pests and diseases, improve yields and enhance product quality (Mohapatra et al., 2024). In Africa, the demand for improved okra varieties is increasing, making them more resistant to pests and diseases (Ibitoye & Kolawole, 2022). Investment in agricultural research has supported the development of improved okra varieties with higher yields, greater resistance to pests and diseases, longer storage potential and improved quality (Banson et al., 2024). Globally, demand for healthy and sustainably produced fruits and vegetables may create opportunities to improve okra production and quality (Nkongho et al., 2022). Okra gardening has been increasingly popular in recent years as more individuals become interested in growing their own fruits and vegetables, seeking out sustainable and healthful options (Sorapong, 2012). As a result, new okra varieties have been produced, which are better adapted to local climates and soils, producing high-quality crops and improving yields (Makinde et al., 2022). Okra fruits are soft, rich in mucilage and tasty (Maria et al., 2015).

Okra is a source of dietary polysaccharides, protein, vitamins and minerals. Its mineral composition includes potassium, calcium, magnesium, iron and zinc, while its vitamin content includes vitamins A and B group vitamins (Elkhalifa et al., 2021). Okra also has a high fibre content and unsaturated fatty acids and is rich in natural phytochemicals, including phenolic compounds, antioxidants, phenolic acids, flavonoids and anthocyanins, as well as vitamins C, E and carotenoids (Techavuthiporn et al., 2024). Antioxidants, such as polyphenols and vitamins C and E, are substances that significantly prevent the oxidation of a substrate and are used as protective agents against oxidation (Rababah et al., 2023).

The main edible part of the plant is its immature green pods. These pods can be boiled, stir-fried, grilled or added to soups and stews, where their mucilaginous texture acts as a natural thickening agent (Dantas et al., 2021). The entire plant is edible. The fresh leaves can be used in salads or cooked like other leafy vegetables, such as beets and dandelions (Swamy, 2023). In West Africa, people grind dried okra pods into powder to help preserve them and ensure they are available during food shortages. In Turkey, they sun-dry the pods for winter use (Ofori et al., 2020). The crop also has health benefits, and there is growing interest in its antioxidant, antidiabetic and antimicrobial properties (Dantas et al., 2021). The Centre for Agriculture and Bioscience International (CABI, 2022) has identified that Asia and Africa dominate okra production by 67% and 33% globally, while the highest okra-producing countries are India and Nigeria, each at 75% and 25%, respectively.

Despite its numerous benefits, okra remains highly perishable, primarily due to its high moisture content, which ranges between 80-90%, making it particularly susceptible to post-harvest deterioration. The reality is that okra post-harvest losses continue to be significant, especially in regions lacking access to adequate cold chain infrastructure (El-Shaieny et al., 2022). Conventional preservation methods such as traditional sun drying, air drying or hot air drying are commonly employed. These methods are often associated with nutrient degradation and poor sensory quality (Calín-Sánchez et al., 2020). Specifically, conventional drying compromises the texture, flavour and colour of okra, making the end product less appealing to consumers. Such techniques also often fail to achieve sufficient dehydration, thereby increasing the risk of microbial contamination (Blessing & Richard, 2022). Consequently, a wide range of post-harvest interventions, including cold storage, freezing, chemical treatments, modified atmosphere packaging (MAP), edible coatings and drying technologies, have been investigated to mitigate quality losses and to extend its shelf life.

Previous studies and reviews have examined specific aspects of okra preservation, such as nutritional composition, drying kinetics and general post-harvest management practices (Blessing & Richard, 2022; Rababah et al., 2023). The current literature largely examines preservation methods in isolation, with minimal comparative analysis of quality retention, sensory performance and techno-economic implications. In particular, few reviews systematically evaluate preservation strategies using a unified comparison approach that integrates nutrient retention, microstructural integrity, rehydration behaviour, sensory acceptability and energy/cost considerations. This gap complicates evidence-based decision-making for researchers, processors and practitioners operating under various resource limitations.

Among the emerging preservation techniques, freeze-drying has attracted increasing attention due to its ability to preserve cellular structure, bioactive compounds and sensory attributes compared to conventional drying methods (Waghmare et al., 2023). Nevertheless, its acceptance for okra remains limited, primarily due to its high capital and energy requirements, secondarily because performance evaluations related to alternative methods are scattered across studies using diverse methodologies. The relative benefits and limitations of freeze-drying in the larger context of okra post-harvest management are still unclear in the absence of comprehensive synthesis.

The aims of this review are to provide a structured and critical comparative analysis of major post-harvest processing and preservation techniques for okra. Preservation strategies are systematically classified into physical, chemical and processing methods and assessed using a harmonised framework that includes nutritional retention, texture and microstructure, rehydration and functional properties, sensory quality and energy/cost implications. Specific emphasis is placed on freeze-drying, not as a universal solution,

but as a benchmark technology against other approaches which are critically examined. By synthesising evidence across studies and identifying methodological limitations and research gaps, this review aims to support informed technology selection, guide future research and facilitate context-appropriate adoption of post-harvest preservation strategies for okra.

## REVIEW METHODS

A systematic literature review was conducted using the protocol, search, appraisal, synthesis, analysis and reporting (PSALSAR) framework (Mengist et al., 2020). The literature search covered peer-reviewed research articles, conference proceedings and review papers published between years 2010 and 2025. Searches were conducted in Web of Science, Scopus and Google Scholar between October to December 2025 using combinations of keywords including "okra", "*Abelmoschus esculentus*", "post-harvest", "storage", "drying", "freeze-dry", "1-MCP", "modified atmosphere packaging", "calcium chloride", "coating" and "evaporative cooling". The Boolean operator OR was used to combine related keywords and synonyms within each search concept, while AND was used to combine okra-related terms with post-harvest preservation and processing terms. Database-specific search fields and syntax were applied in Web of Science and Scopus, whereas separate keyword queries were used in Google Scholar. The database-specific search strategies and corresponding search terms are presented in Supplementary Table S1. Duplicate records were removed before title and abstract screening. Potentially relevant articles were assessed in full text against the inclusion and exclusion criteria. The inclusion criteria were: (a) primary experimental studies on okra or closely related vegetables that report quantitative outcomes for at least one preservation method, (b) reporting at least one of the following quality metrics, *i.e.* nutrient/phenolic retention, texture/microstructure, rehydration potential, sensory acceptability and energy/cost parameters. Studies that only provided qualitative information or lacked quantitative data were used for contextual background but omitted from the comparative table. The literature selection process is summarised in Figure 1. The included studies were examined for methodological clarity, replication, reporting transparency and relevance to the review objectives. These considerations informed the qualitative synthesis of the available evidence. Findings were synthesised qualitatively, with preservation methods compared across nutrient retention, texture and microstructure, rehydration, sensory acceptability, and energy/cost considerations. The ratings describe relative performance reported in the literature rather than numerical scores or formal assessments of study quality. The scope of the completed review was retrospectively mapped to the Population, Intervention, Comparison, Outcomes and Context (PICOC) framework to clarify its objectives during manuscript preparation. The PICOC framework and database-specific search strategies are listed in Supplementary Table S1.

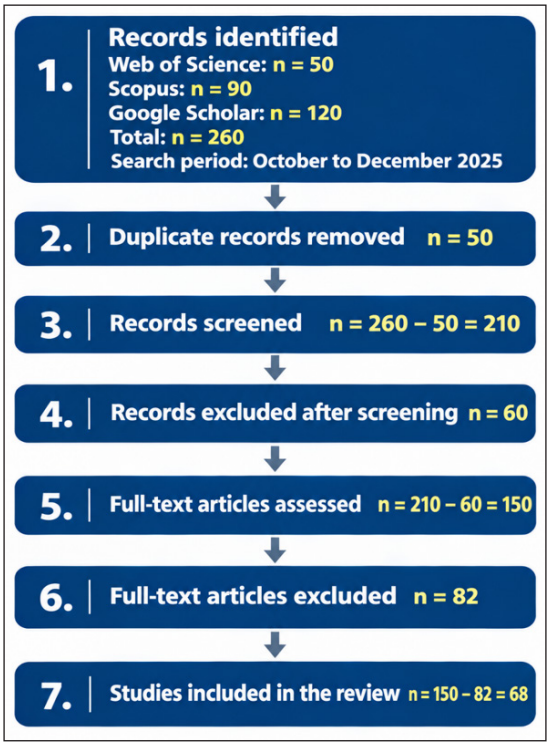


*Figure 1*. Flow diagram of the literature identification, screening, eligibility assessment and study selection process for the review of post-harvest preservation methods for okra (*Abelmoschus esculentus* L.).
*Note*. Records were excluded if they were outside the scope of okra post-harvest preservation or did not meet the inclusion criteria. Full-text articles were excluded if they lacked relevant experimental findings or sufficient information on the preservation methods and quality indicators assessed in this review

## POST-HARVEST TREATMENTS OF OKRA

Post-harvest handling is essential for prolonging the shelf life and preserving the quality of okra, which deteriorates rapidly after harvest. In this review, post-harvest preservation treatments are organised into three categories, i.e. (1) Physical methods, (2) Chemical methods and (3) Processing methods involving drying or packaging. This classification provides a practical basis for comparing methods according to their principal interventions and intended preservation functions. Physical methods involve controlling storage conditions or applying physical treatments to harvested produce, including cold storage, controlled atmosphere storage, freezing, hot-water treatment with blanching and evaporative cooling (Usall et al., 2016). Chemical methods involve applying compounds that regulate physiological processes, maintain tissue integrity or control microbial deterioration, including 1-methylcyclopropene (1-MCP), calcium chloride, edible coatings and sanitising chemicals. These treatments have also been discussed in the context of okra preservation by Blessing and Richard (2022). Processing methods involving drying or

packaging encompass techniques that reduce moisture content or modify the atmosphere surrounding the product. These include modified atmosphere packaging (MAP), drying using sun, hot air or microwave heating and freeze-drying or hybrid freeze-drying (Hasan et al., 2019; Sandhya, 2010). Although these methods may involve overlapping preservation mechanisms, they are grouped according to their principal intervention in this review. The following subsections examine their preservation principles, effects on product quality, practical feasibility and limitations, with particular attention to the process parameters and techno-economic considerations of freeze-drying.

## PHYSICAL METHODS

### Cold Storage and Controlled Atmosphere Storage

Cold storage slows respiration, reduces water loss and limits microbial activity, thereby helping to maintain texture and colour. Okra is typically stored at 8-10 °C and 85-90% relative humidity, extending its shelf life to about 8-10 days. Controlled atmospheric storage with decreasing $O_2$ to about 3-5% and enriching $CO_2$ to 5-10% can delay senescence by reducing ethylene activity. Studies report that okra preserved under such atmospheres retains chlorophyll and firmness longer than samples in ambient storage. Key limitations include chilling injuries below 7 °C and the necessity for temperature-regulated infrastructure (Blessing & Richard, 2022). Overall, cold storage is useful for short-term management but not for long-term preservation.

Despite consistent reports of delayed senescence under cold and controlled atmosphere storage, comparisons between studies are complicated by variations in storage temperature, gas composition, cultivar and maturity stage at harvest. Many studies report that quality retention without measuring biochemical degradation kinetics limits mechanistic interpretation and cross-study comparability. The practical relevance of controlled atmosphere storage is also limited in low-resource environments where temperature regulation and gas control facilities are inconsistent.

### Freezing

Freezing reduces enzymatic and microbial activity by lowering temperature and limiting the availability of liquid water (Admane & Karadbhajne, 2019). Rapid freezing creates small ice crystals which reduce cell rupture and improve rehydration after thawing. Studies suggest that freezing can preserve phenolic compounds and antioxidant capacity more effectively than some conventional drying methods. Al-Dabbas et al. (2023) reported that blanching followed by freezing provided favourable retention of phenolic compounds and antioxidant activity compared with the oven- and sun-drying treatments. However, freezing does not completely prevent phytochemical degradation during storage. Rababah et al. (2023) reported reductions in total phenolic, flavonoid and anthocyanin contents and

antioxidant activity in both air-dried and frozen okra during six months of storage. The major limitations of freezing include energy requirements, cold-chain maintenance and textural softening upon thawing.

### Heat Treatment by Hot Water or Blanching

Blanching is commonly applied before drying to inactivate enzymes associated with quality deterioration and improve colour retention. Blanching deactivates oxidative enzymes like polyphenol oxidase and peroxidase. For okra, hot-water blanching at 90 °C for 3 minutes has been investigated as a pretreatment to improve the colour and quality of dried products. However, excessive thermal exposure may adversely affect heat-sensitive nutrients and tissue characteristics (Potisate et al., 2026). Hydrothermal treatment has also been investigated as a pre-storage treatment for fresh okra. Ribeiro et al. (2017) reported delayed surface browning in hot-water-treated pods during refrigerated storage, with changes in polyphenol oxidase activity.

### Evaporative Cooling and Other Low-Cost Physical Treatments

Evaporative cooling lowers produce temperature through the evaporation of water from a porous surface, offering a relatively low-energy preservation option for smallholders. Clay pot coolers or charcoal coolers can keep okra at 12-15 °C under hot tropical conditions, doubling its shelf life compared to ambient storage (Lal-Basediya et al., 2013). However, the system requires low ambient humidity and regular water replenishment. Other low-cost approaches include perforated plastic crates and shaded storage, which mainly slow physical deterioration rather than biochemical degradation.

## CHEMICAL METHODS

### Application of 1-Methylcyclopropene (1-MCP)

1-MCP is an ethylene action inhibitor that binds to ethylene receptors, which slows ripening and senescence. Kanwal et al. (2020) examined 1-MCP and modified atmosphere packaging, both individually and in combination during storage at ambient and low temperatures. The combined treatment helped maintain visual quality and limit softening, weight loss and deterioration of selected quality attributes. The effectiveness of 1-MCP depends on application conditions, storage temperature and its combination with other preservation treatments.

### Application of Calcium Chloride ($CaCl_2$)

Calcium ions strengthen cell walls by forming calcium pectate bridges in the middle lamella, which reduces softening. Dipping okra pods in 1-2% $CaCl_2$ solution for 5-10

minutes improves firmness and reduces microbial deterioration during storage at 10°C. Additionally, $CaCl_2$ delays colour change, which stabilises membrane permeability (Yahia et al., 2019). Calcium chloride treatment is affordable and can be combined with other preservation approaches such as MAP and edible coatings. However, concentrations that are greater than 3% may result in surface spotting or bitterness.

### Application of Edible Coatings and Sanitising Chemicals

Edible coatings, including chitosan, aloe vera, gum arabic, starch or pectin, function as semipermeable barriers to gas and moisture exchange. Coated okra pods exhibit reduced weight loss and slower colour degradation compared to uncoated controls. Chitosan coatings have been investigated as a means of maintaining the quality of stored okra. Li et al. (2015) compared chitosan concentrations of 0.5%, 1.0% and 1.5% and reported that the 1.0% treatment provided the best quality retention among the tested treatments during storage at approximately 20 °C. The treatment delayed chlorophyll loss and reduced respiration intensity and indicators of membrane deterioration. Sanitising chemicals (e.g. sodium hypochlorite 100 ppm) are often used before coating to reduce microbial load. The coating methods are scalable, but its film uniformity and consumer acceptance require optimisation.

While chemical treatments are normally described as cost-effective and easy to apply, their reported benefits are often incremental rather than transformational. Limited attention is given to consumer perception, regulatory approval and cumulative effects when multiple treatments are combined, highlighting the need for more integrated evaluation frameworks. The shelf-life extension was measured in days rather than weeks, and treatment efficacy is highly influenced by initial fruit quality and storage conditions.

## PROCESSING METHODS VIA DRYING OR PACKAGING

### Modified Atmosphere Packaging (MAP)

MAP involves altering gas composition around the product by reducing $O_2$ and increasing $CO_2$. Packaging film characteristics can influence the post-harvest quality of refrigerated okra. Paulus et al. (2021) compared LDPE films of different thicknesses with unwrapped pods stored at 10 ± 1 °C. At 21 days, the packaged okra generally showed lower mass loss, greater firmness and less colour change than the unwrapped control. Among the films tested, the 30 μm LDPE film provided favourable retention of several quality attributes. The combining of MAP and refrigeration further improves chlorophyll and ascorbic acid retention. Small-holders face challenges such as condensation build-up, uneven gas distribution and high film cost.

## Conventional Drying Using Sun, Hot Air or Microwave

Drying reduces water activity below microbial growth thresholds but may degrade heat-sensitive nutrients. Unprotected sun drying may increase exposure to contamination and colour darkening. Li et al. (2019) investigated hot-air drying of okra at 55-80 °C and found that drying temperature and cutting orientation influenced drying behaviour and product quality. Compared with hot-air drying, heat-pump drying provided better overall quality under the conditions investigated. Although conventional drying remains attractive due to its low capital requirement, reported quality outcomes vary greatly between studies, reflecting differences in drying temperature, airflow, slice thickness and pre-treatment techniques. Many studies compare nutrient retention to fresh samples without accounting for concentration effects caused by moisture loss, which can lead to overestimation or underestimation of degradation. These methodological differences limit comprehensive comparison with advanced drying techniques and highlight the need for standardised reporting.

## Freeze-Drying or Hybrid Freeze-Drying

### *Principle and Process Parameters*

Among the processing methods reviewed, freeze-drying stands out for its improved preservation efficiency, which is discussed in greater detail below to illustrate its comparative advantages and limitations. Freeze-drying consists of three stages, which are freezing, primary drying (sublimation) and secondary drying (desorption) under vacuum (Coşkun et al., 2024). Rapid freezing produces small ice crystals, which protect cell integrity. Slow freezing causes large crystals that rupture membranes and reduce textural quality. Key parameters influencing outcomes include freezing rate, chamber pressure (usually <100 Pa), shelf temperature ranging from -40 to +30 °C across stages and drying duration. Optimised conditions provide highly porous structures and excellent rehydration properties (Zheng et al., 2024). Table 1 summarises the freezing temperatures, drying times and vacuum pressures reported for freeze-drying different fruits and vegetables, including okra. The reported conditions vary considerably among commodities, reflecting differences in the materials being dried and the processing conditions used in the respective study. For okra, the studies listed in Table 1 report freezing temperatures ranging from -20 to -30 °C, drying times of 3 and 24 hours and vacuum pressures of 51.8 and 20 Pa (Xu et al., 2021; Jiang et al., 2017). These differences highlight the importance of considering specific operating conditions reported in each study when evaluating freeze-drying performance. However, direct comparisons of drying time and pressure should be interpreted cautiously because differences in sample preparation, pre-treatment, equipment configuration and final moisture content may also influence the reported results.

Table 1
*Freeze-drying parameters for different types of fruits and vegetables*

| Type of Fruit/ Vegetable | Freezing Temperature (°C) | Drying Time (hr) | Vacuum Pressure (Pa) | References |
|---|---|---|---|---|
| Apple | -25 | 24 | 45-82 | Antal et al., 2013 |
| Avocado | -40 | 72 | 13.3 | Castañeda-Saucedo et al., 2014 |
| Banana | -18 | 24 | 45 | Milani et al., 2020 |
| Blackberries | -75 | 24 | 99.8 | Oliveira et al., 2023 |
| Blueberries | -76 | 24 | 0.1 | Ochmian et al., 2020 |
| Carrot | -15 | 14 | 10 | Acar et al., 2021 |
| Ginger | -20 | 24 | 50 | Buvaneswaran et al., 2021 |
| Kiwifruit | -35 | 21 | 133.322 | Wang et al., 2022 |
| Mushroom | -20 | 48 | 20 | Yang et al., 2019 |
| Okra | -20/-30 | 3 and 24 | 51.8, 20 | Xu et al., 2021; Jiang et al., 2017 |
| Onion | -47 to -50 | 38 | 0.666 | Guiné & Barroca, 2010 |
| Papaya | -25 | 24 | 77, 28, 9 | Udomkun et al., 2018 |
| Pineapple | -50 | 2 | 52 | Izli et al., 2018 |
| Pumpkins | -30 | 24 | 10 | Chao et al., 2023 |
| Raspberry | -20 | 48 | 0.88 | Stamenković et al., 2019 |
| Red bell pepper | -40 | 4 | 63 | Rybak et al., 2021 |
| Soursop | -45 | 6 | 133 | Ceballos et al., 2012 |
| Tomato | -20 | - | 10 | Lopez-Quiroga et al., 2020 |
| Yam | -60 | 48 | 60 | Lin et al., 2014 |

### *Evidence for Okra and Analogous Vegetables*

The reviewed studies show that freeze-dried okra retains higher levels of phenolic compounds, vitamin C and flavonoids compared to hot air- or sun-dried counterparts. Comparative studies on onions and leafy vegetables indicate that the effects of drying on bioactive compounds and physical quality depend on the commodity, compound and drying conditions, rather than demonstrating a consistent advantage for one method across all attributes (Ren et al., 2018; Vargas et al., 2022). Recent innovations using hybrid microwave freeze-drying and infrared-assisted freeze-drying could reduce drying time by up to 50% while maintaining comparable quality (Al Faruq et al., 2025).

### *Practical Considerations for Okra*

The mucilaginous texture of okra and seed distribution influence heat and mass transfer during freeze-drying. Pre-treatments such as slicing or blanching before freezing can influence drying behaviour and final product quality (Nowak & Jakubczyk, 2020). Hybrid

Table 2
*Qualitative comparison of preservation methods in terms of nutrient retention, texture, microstructure and rehydration, sensory acceptability, and energy/cost requirement*

| Preservation Method | Nutrient Retention | Texture/Microstructure /Rehydration | Sensory Acceptability | Energy/Cost Requirement |
|---|---|---|---|---|
| Cold storage | Moderate | Good (fresh-like) | High | Low |
| Freezing | High | Good | High | Low-Moderate |
| Heat treatment | Moderate-Low | Variable | Moderate | Low |
| 1-MCP | Moderate | Good | High | Low |
| $CaCl_2$ application | Moderate | Good | Moderate | Low |
| Edible coatings | Moderate | Good | Moderate | Low |
| MAP | Moderate | Good | Moderate-High | Moderate |
| Conventional drying | Low | Poor-moderate | Moderate | Low |
| Freeze-drying | Very High | Very Good | High | High |

*Note*. The ratings refer to relative performance and do not represent predefined numerical thresholds

techniques such as microwave freezing, infrared freezing, and ultrasonic combination with freeze-drying may lower the cost and time, but they require validation for okra quality traits. Pre-treatment optimisation, including calcium dips or osmotic dehydration, can further enhance nutritional stability and rehydration.

Table 2 presents a comparative finding highlighting the distinct advantages and trade-offs among the different preservation techniques from various references (Al Faruq et al., 2025; Chacha et al., 2021; Ismail et al., 2019; Kwadzo et al., 2022; Lisboa et al., 2024; Maurya, 2025; Sharma et al., 2024; Sridhar et al., 2021; Wang et al., 2019). Freeze-drying can offer advantages in selected nutritional, structural and sensory attributes, but its application is constrained by high costs and energy requirements (Nwankwo et al., 2023). Cold storage and freezing maintain fresh-like quality, while chemical methods offer limited shelf-life extension with low infrastructure needs. Solar-assisted pre-drying may reduce moisture load entering the freeze-dryer, potentially reducing the subsequent drying load, although its feasibility depends on the drying system and operating conditions (Venkateswarlu & Reddy, 2024). Infrared-assisted freeze-drying has demonstrated potential to reduce drying time and energy consumption in studies on banana products (Khampakool et al., 2019). Ultrasound-assisted freeze-drying is particularly relevant to okra because its potential benefits have been investigated directly. Xu et al. (2021) reported that ultrasound and freeze-thaw pre-treatments reduced vacuum freeze-drying time by 25.0-62.5% and total energy consumption by 24.28-62.35%, depending on the pre-treatment applied. The study also reported retention of several quality characteristics, including colour, flavour and texture. These findings suggest that ultrasound-assisted pre-treatment may improve the processing efficiency of freeze-dried okra, although the results depend on the treatment

conditions (Xu et al., 2021). More broadly, Waghmare et al. (2023) reviewed the potential of ultrasonic pre-treatment to improve drying rate, shorten processing time and reduce energy consumption during freeze-drying of food materials. However, the energy savings, effects on okra quality and economic feasibility of these approaches require experimental validation before they can be recommended for commercial okra processing. A reliable comparison of processing costs per kilogram of fresh okra and equipment payback periods requires information on equipment investment, energy consumption, labour, maintenance, processing capacity and product yield. Future research should compare conventional and hybrid drying systems using consistent measures of specific energy consumption, processing cost and economic return to assess their suitability for small- and medium-scale processors.

Although conventional drying is relatively affordable, it may compromise nutritional quality compared with freeze-drying. For short-term household handling, low-cost physical methods such as evaporative cooling remain practical. Medium-scale processors benefit from MAP or calcium treatments when moderate shelf life is needed. Freeze-drying, while capital-intensive, is best suited for high-value or export-oriented okra products. The comparative ratings in Table 2 represent a qualitative synthesis of the findings reported in the reviewed literature, rather than measurements obtained using a standardised numerical scoring system. The categories were used to summarise the relative performance of preservation methods across nutrient retention, texture, sensory acceptability, and energy/cost considerations. The assessment criteria and supporting evidence were considered for each method, while recognising that differences in experimental conditions and measurement approaches limit direct comparisons between studies. The use of qualitative categories is intended to make the comparison accessible and transparent, rather than imply precise or universally applicable rankings. Such comparative assessment is consistent with food-processing reviews that evaluate technologies using product quality, processing performance, energy efficiency and cost considerations (An et al., 2024; Asrate & Ali, 2025). As summarised in Table 2, freeze-drying offers advantages in nutrient retention, structural preservation and rehydration performance compared with conventional drying methods, although the extent of these benefits depends on the processing conditions and the quality attributes evaluated. Figure 2 illustrates the freeze-drying equipment and its operating principle, combining a photograph of the equipment with a schematic representation of its major components and process flow. Freeze-drying can offer advantages in nutrient retention, structural preservation and rehydration performance compared with conventional drying, although the extent of these advantages depends on the food material, processing conditions and quality attributes measured. Despite its improved quality retention, its technological complexity, long processing durations and high energy demand limit its applicability to high-value or niche markets. Process optimisation or hybridisation strategies

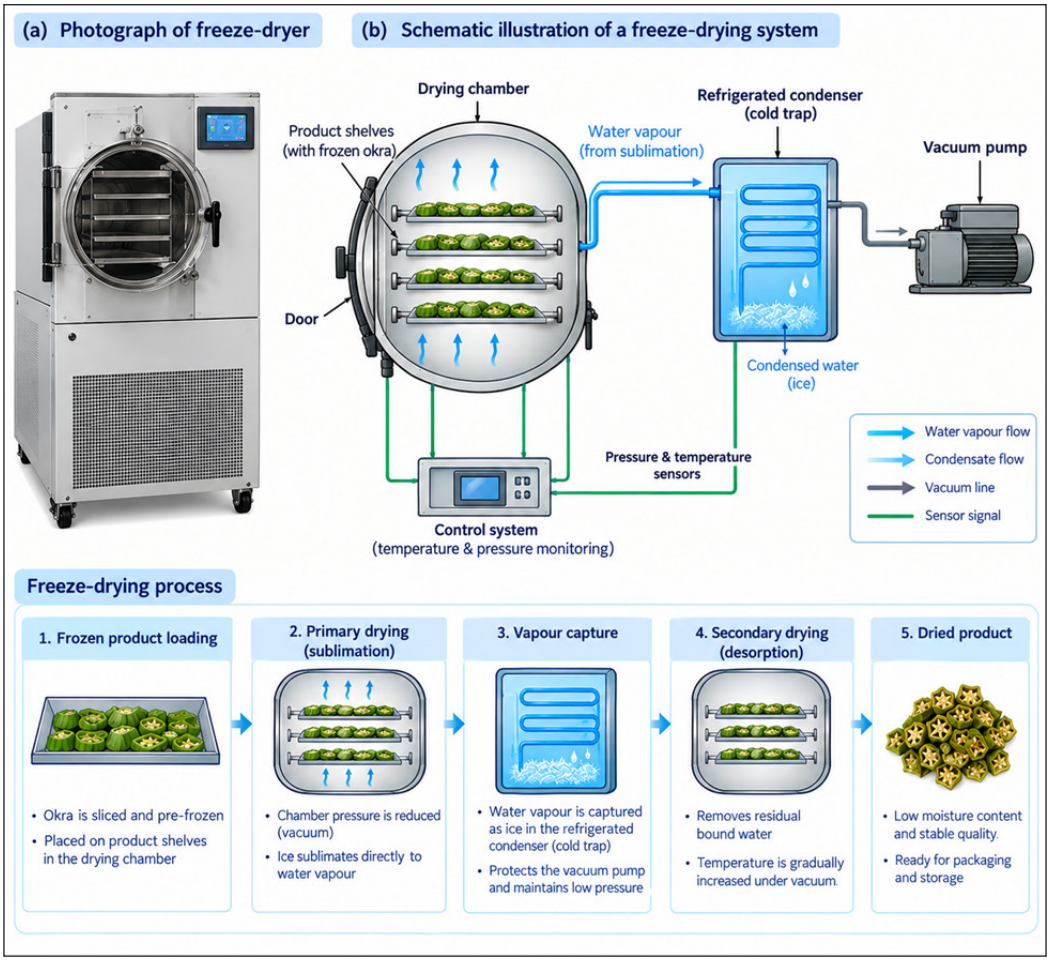


*Figure 2.* Freeze-drying equipment and operating principle: (a) photograph of a freeze-dryer; (b) schematic illustration of the major components

are required for successful implementation; thus, the suitability of freeze-drying must be evaluated within specific economic, infrastructural and market contexts rather than just on quality parameters.

## Techno-Economic Considerations of Freeze-drying

Implementing freeze-drying for okra requires large capital and operating costs. Freeze-drying involves substantially higher equipment, operational and maintenance costs than conventional hot-air drying, with reported costs approximately four to eight times higher. In a typical freeze-drying process, sublimation accounts for approximately 45% of the total energy cost, while vacuum generation, condensation and freezing account for approximately 26%, 25% and 4%, respectively (Nwankwo et al., 2023). These estimates are not specific

to okra, and their applicability depends on equipment configuration, processing scale and operating conditions. Hybrid systems of microwave, infrared and ultrasound-assisted systems may have the ability to reduce energy usage while preserving product quality, although their performance requires further validation. Practical feasibility in developing regions requires modular systems, pre-treatments to reduce load and energy-efficient operation. Economic viability depends on market price, product value addition and energy/cost structures. Techno-economic interpretation is limited by a lack of complete energy/cost balance data reports. Small sample sizes and varied analytical assays restrict quantitative synthesis. Further research should apply standardised protocols and report comprehensive metrics including cost, energy and quality retention to support decision-making.

## CONCLUSION AND FUTURE DIRECTIONS

Cold storage is the most commonly used method of post-harvest management for okra, especially when combined with treatments such as heat application or calcium chloride. Physical methods such as plastic wrapping or evaporative cooling provide low-cost alternatives, while chemical methods and advanced process technology such as freeze-drying have potential as a novel technique for maintaining the nutritional value, sensory qualities and shelf life of okra as reviewed in this paper. It is a potential alternative to conventional preservation techniques in reducing post-harvest losses, increasing food security and promoting the long-term growth of vegetable preservation techniques. Freeze-drying remains an effective method for processing okra because it can retain selected quality attributes of okra and produce porous products with good rehydration properties. However, its advantages vary with the quality attribute, pre-treatment, operating conditions and intended product. Its high capital and operating costs should be considered alongside the requirements of the target market and the available alternatives.

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## SUPPLEMENTARY TABLE

Table S1
*Part A: Database-specific search strategies and Part B: Retrospective PICOC mapping*

| Part A Database | Search String |
|---|---|
| Web of Science | TS = (okra OR "Abelmoschus esculentus") AND<br>TS = ("post-harvest" OR "preservation" OR "storage" OR "drying" OR "freeze-drying" OR "lyophilisation" OR "modified atmosphere packaging" OR "1-MCP" OR "calcium chloride" OR "coating" OR "evaporative cooling") |
| Scopus | TITLE-ABS-KEY ("okra" OR "Abelmoschus esculentus") AND<br>TITLE-ABS-KEY ("post-harvest" OR “preservation" OR "storage" OR "drying" OR "freeze-drying" OR "lyophilization" OR "modified atmosphere packaging" OR "1-MCP" OR "calcium chloride" OR coating OR "evaporative cooling") |
| Google Scholar | Run separate searches using the following queries:<br>(1) "okra" OR "post-harvest" preservation;<br>(2) "Abelmoschus esculentus" OR "drying" OR "freeze-drying";<br>(3) "okra" OR "modified atmosphere packaging" OR "edible coating",<br>(4) "okra" OR "1-MCP" OR "calcium chloride" OR "evaporative cooling". |
| **Part B Component** | **Scope** |
| Population (P) | Harvested okra pods (*Abelmoschus esculentus* L.). Studies on other vegetables provide supporting evidence where okra-specific evidence is limited and are distinguished from direct evidence on okra. |
| Intervention (I) | Physical and chemical preservation treatments, modified atmosphere packaging, conventional drying, freeze-drying and hybrid freeze-drying. |
| Comparison (C) | Alternative preservation methods, untreated controls or different treatment conditions, where available. |
| Outcomes (O) | Nutrient and bioactive compound retention, texture and microstructure, rehydration and functional properties, sensory quality and shelf life. Energy consumption and processing costs are considered secondary outcomes where reported. |
| Context (C) | Postharvest storage and processing of okra, with consideration of technical feasibility and resource availability. |