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PRESERVING SPICE QUALITY FROM HARVEST TO SHELF: POST-HARVEST TECHNOLOGIES AND MOLECULAR STRATEGIES FOR SHELF-LIFE EXTENSION

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ABSTRACT:
Seed spices play a vital role in the agricultural economy and global trade due to their culinary, medicinal, and industrial importance. However, significant post-harvest losses occur at various stages including harvesting, drying, threshing, storage, transportation, and processing, leading to substantial reductions in both quality and quantity. These losses are primarily attributed to improper harvesting practices, inadequate drying, high moisture content, microbial contamination, insect infestation, and poor storage and packaging systems. The present article comprehensively reviews the general and crop-specific strategies to overcome post-harvest losses in major seed spices such as coriander, cumin, fennel, fenugreek and others. Emphasis is placed on scientific harvesting, improved drying techniques including solar and mechanical drying, efficient threshing and grading, and the adoption of hermetic and controlled storage systems. The role of eco-friendly pest management practices, modern packaging technologies such as vacuum and modified atmosphere packaging, and value addition through processing is also highlighted.
Furthermore, the article discusses emerging technologies such as Molecular based strategies, IoT-based monitoring systems, artificial intelligence, and blockchain to enhance the post-harvest efficiency and traceability. Future prospects focus on sustainable and climate-resilient post-harvest management approaches, including the use of biodegradable packaging, botanical preservatives, and decentralized processing infrastructure. The importance of farmer awareness, capacity building, institutional support, and the role of Farmer Producer Organizations (FPOs) in reducing losses is also emphasized. Overall, an integrated post-harvest management approach combining technological innovation, sustainable practices, and policy support is essential to minimize losses, improve quality, extend shelf life, and enhance the economic returns and export potential of seed spices.

KEYWORDS: Post-harvest losses, Seed spices, Storage management, Drying techniques, Value addition

INTRODUCTION

Post-harvest processing is a critical stage in maintaining the quality, safety and market value of seed spices because it directly influences the retention of flavour, aroma, nutritional constituents and bioactive compounds. Major seed spices include cumin (Cuminum cyminum L.), coriander (Coriandrum sativum L.), fennel (Foeniculum vulgare Mill.), fenugreek (Trigonella foenum-graecum L.), ajwain (Trachyspermum ammi L.), dill (Anethum graveolens L.) and nigella (Nigella sativa L.). Besides their culinary importance, these crops are rich sources of essential oils, oleoresins, phenolics, flavonoids and other phytochemicals with applications in the food, pharmaceutical, nutraceutical and cosmetic industries 1. India is a major producer, consumer and exporter of spices. During 2025–26, the country exported 17.34 lakh tonnes of spices and spice products valued at ₹39,140.11 crore (US$4.43 billion), highlighting the substantial economic importance of the spice sector. Cumin and coriander are among the important seed spices contributing to this export value2.

Despite their relatively low moisture content, seed spices are highly vulnerable to post-harvest deterioration because their quality depends strongly on the preservation of volatile oils and other chemically reactive constituents. Harvesting at inappropriate maturity, mechanical injury during threshing, inadequate drying, microbial contamination, insect infestation and improper storage can result in both quantitative and qualitative losses. A national assessment by ICAR–CIPHET and NABCONS estimated harvest and post-harvest losses of 1.29–7.33% for the combined category of plantation crops and spices during 2020–223. Although this estimate is not specific to individual seed spices, experimental storage studies demonstrate that losses can become substantial under favorable pest conditions; cigarette beetle (Lasioderma serricorne) infestation, for instance, has been associated with damage levels of approximately 58.02% in fennel and 39.0% in dill under experimental conditions 4,5. Importantly, post-harvest losses in spices extend beyond physical weight reduction and include deterioration of colour, aroma, essential-oil composition, nutritional quality and microbial safety.

The principal factors governing seed-spice shelf life are moisture, temperature, oxygen, light, insects, microorganisms and endogenous biochemical reactions. High moisture and water activity promote fungal growth and enzymatic activity, whereas elevated temperature accelerates respiration, lipid oxidation and loss of volatile compounds. Oxygen facilitates oxidative degradation of unsaturated lipids and aroma constituents, leading to rancidity and off-flavour development6. Therefore, post-harvest technologies must simultaneously control moisture, temperature, oxygen and microbial or insect contamination while preserving desirable phytochemicals.

An effective post-harvest management system begins with harvesting at optimum maturity, followed by efficient threshing, cleaning, grading and drying. Drying is particularly important because rapid reduction of seed moisture to a safe level suppresses microbial proliferation and slows biochemical deterioration 7. Conventional and advanced techniques, including controlled hot-air, solar-assisted, microwave, vacuum-microwave, infrared and hybrid drying, can improve drying efficiency and product quality. For example, studies in Coriandrum sativum demonstrated that convective drying at 70°C for 120 min followed by vacuum-microwave drying provided favourable retention of volatile compounds and sensory quality8. Following drying, appropriate cleaning and grading reduce foreign material and damaged seeds, while moisture- and oxygen-barrier packaging, vacuum packaging, hermetic storage and modified-atmosphere packaging can minimize moisture migration and oxidative deterioration 9. Controlled temperature and relative humidity, together with integrated insect-management practices, further improve storage stability.

Microbial decontamination is another important component of spice preservation. Gamma irradiation, ozone, ultraviolet treatment and natural antimicrobial agents have demonstrated potential for reducing microbial loads without the extensive use of chemical preservatives 10. Gamma irradiation, in particular, can effectively reduce bacterial, yeast and mould populations in spices when applied at optimized doses. However, treatment intensity must be carefully controlled because excessive exposure may influence colour, aroma and essential-oil composition 9. Combining decontamination treatments with suitable packaging and controlled storage conditions can provide synergistic protection and extend shelf life.

In parallel with post-harvest technologies, molecular approaches provide opportunities to address the biological mechanisms underlying quality deterioration and storage stability. Genomics, transcriptomics, metabolomics and proteomics can identify genes, enzymes and metabolic pathways associated with essential-oil biosynthesis, antioxidant defence, lipid metabolism, stress responses and resistance to storage pests and pathogens. In seed spices, the regulation of terpenoid and phenylpropanoid pathways is particularly important because these pathways govern the production of characteristic volatile and phenolic compounds. Molecular characterization can also facilitate the identification of genotypes possessing higher antioxidant capacity, desirable essential-oil profiles and improved resistance to biotic and abiotic stresses.

At the cellular level, antioxidant systems involving superoxide dismutase, catalase, ascorbate peroxidase and glutathione-dependent enzymes play important roles in limiting reactive oxygen species-mediated membrane and lipid damage during storage. Molecular breeding, marker-assisted selection, transcriptome-guided selection and metabolite profiling can therefore complement conventional post-harvest interventions by identifying and utilizing genotypes with superior storage stability 11. Emerging genome-editing technologies may further provide opportunities to modify specific genes regulating lipid oxidation, volatile-compound metabolism, antioxidant defense and stress tolerance.

Thus, sustainable extension of seed-spice shelf life requires an integrated post-harvest and molecular strategy. Optimized harvesting, drying, decontamination, packaging and storage can minimize immediate physical, microbial and biochemical losses, whereas molecular approaches can elucidate and exploit the genetic and metabolic mechanisms governing long-term quality retention. Integrating these approaches is essential for preserving essential oils, aroma, colour, phytochemicals and microbial safety, thereby reducing post-harvest losses and enhancing the quality, shelf life and commercial value of major seed spices.

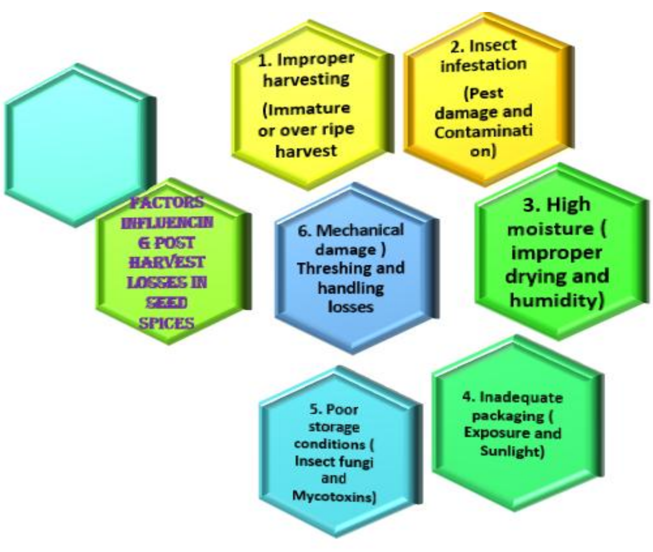

Fig 1 Factors influencing post-harvest losses in seed spices

Global status of seed spices

The global seed spices market primarily comprising cumin, coriander, fennel, fenugreek, and ajwain forms a crucial segment of the international spice trade, with India maintaining overwhelming dominance by contributing nearly 75% of global production and earning its reputation as the "Spice Bowl of the World." As part of the broader spices and seasonings industry, the market was valued at USD 24.70 billion in 2024 and is projected to reach USD 37.34 billion by 2032, growing at a CAGR of about 5.3 12. Regionally, the Asia-Pacific leads in production and exports, while North America (holding about 38.69% share in 2025) and Europe serve as major consumption hubs. Ground seed spices are witnessing faster growth (5.7% CAGR) compared to whole spices (0.9% CAGR), driven by rising demand for convenience foods and processed ingredients. Key producing countries include Turkey, Egypt, China, Iran, and Syria, each contributing significantly to specific seed spices, while India leads in exports with a market value of USD 17.28 billion. On the demand side, major importers such as the United States (imports worth about USD 466.08 million), Saudi Arabia (USD 295.29 million), Germany, and Netherlands drive consumption due to the growing popularity of ethnic cuisines and increasing preference for clean-label, natural ingredients 13 Among individual spices, cumin remains the most traded by value with strong recovery trends, coriander has shown steady growth with a 4.3% CAGR in European markets, and fennel maintain stable demand, particularly in beverage and digestive health sectors 14. However, the sector faces emerging challenges such as climate sensitivity especially in key producing regions like Rajasthan and Gujarat along with increasing requirements for sustainability certifications like organic and Fairtrade and the adoption of digital traceability systems by companies such as Olam International

General post-harvest processing in seed spices

Fig 2 Post harvest processing of seed spices

Harvesting should be carried out at physiological maturity, when seeds attain optimum dry matter, characteristic colour and appropriate moisture content. Timely harvesting in coriander, cumin and fennel minimizes shattering while ensuring maximum accumulation of essential oils and flavour compounds; premature harvesting produces poorly developed seeds, whereas delayed harvesting increases field losses and contamination 15 . After harvest, drying is the most critical operation for storage stability, and seed spices are generally dried to about 8–10% moisture, depending on the commodity and storage conditions. Reduction in water activity suppresses microbial growth, respiration and enzymatic activity. Traditional sun drying is economical but may cause uneven drying, contamination and volatile-oil losses. Controlled hot-air, solar, infrared, microwave, vacuum-microwave and hybrid drying systems provide better control of moisture and temperature. In coriander, convective drying at 70°C for 120 min followed by vacuum-microwave drying has been reported to improve retention of volatile compounds and sensory quality 16. Threshing should be performed at optimum moisture to maximize seed recovery and minimize cracking, abrasion and mechanical injury. Mechanized threshers with controlled impact can reduce breakage and improve separation efficiency. Subsequent cleaning and winnowing remove chaff, dust, stones, weed seeds and broken seeds through aspiration, sieving and gravity separation, thereby improving physical purity and reducing microbial and insect contamination 17. Grading based on size, shape, density and colour using mechanical or optical systems improves uniformity, processing efficiency and market value. Polishing, where required, should be carefully controlled because excessive abrasion may damage the seed surface and reduce volatile or bioactive constituents 18

Packaging and storage are essential for maintaining seed-spice quality after processing. Storage should be maintained under low moisture, low temperature and controlled relative humidity to suppress microbial growth, insect infestation, lipid oxidation and volatile-oil losses. Packaging should provide barriers against moisture, oxygen, light and external contamination. Suitable single-layer materials include jute/gunny bags, woven polypropylene, PE, LDPE, HDPE, kraft paper, glass and metal/tin containers. PE, LDPE and HDPE provide effective moisture barriers, whereas glass and metal offer stronger protection against moisture, oxygen and light 19 However, conventional woven bags provide comparatively limited barrier protection and are more suitable for short-term storage under controlled conditions. For longer storage, vacuum and modified-atmosphere packaging can reduce oxygen availability and oxidative deterioration. Active packaging incorporating natural antioxidants or antimicrobial compounds, including selected spice essential oils, represents an emerging shelf-life technology20. Thus, integration of timely harvesting, controlled drying, low-damage threshing, efficient cleaning and grading, appropriate packaging and scientifically managed storage is essential for preserving essential oils, aroma, colour, phytochemicals and microbial safety in seed spices.

Reason for the Post harvest losses in seed spices

Major post-harvest losses (PHL) in seed spices like cumin, coriander, fennel, fenugreek, and ajwain range from 10-25% in India (major producer), occurring from harvesting to storage, driven by traditional practices and leading to economic losses valued in billions. Shattering during harvesting (5-10%): Seeds drop from umbels if harvested immature/overripe or mechanically (e.g., coriander, cumin); manual sickling before central umbels turn greenish-yellow worsens it. Spillage and improper handling (5-15%): Losses from bag tears, rough transport to mandis/mills, unscientific stacking, and teeming; small/marginal farmers (88-90%) hit hardest. Inadequate drying (5-10%): Sun-drying to <10% moisture fails in humid conditions, causing mold/weight loss; delayed drying reduces cumin volatile oil, lowering quality 21

Insect infestation in storage (up to 90% in poor setups): Pests like Tribolium castaneum, Lasioderma serricorne, Callosobruchus spp. in gunny bags; 80-85% farm-saved seeds amplify; weeds pre-harvest cause 80-90% yield loss indirectly. Microbial spoilage and diseases (10-20%): Fungi (Fusarium spp., Rhizoctonia, Erysiphe polygoni causing powdery mildew up to yield losses), bacteria from high moisture/condensation; damping-off/root rot in coriander/cumin/dill/fennel. Threshing /winnowing inefficiencies (3-8%): Manual beating on mud floors contaminates with aflatoxins/microbes; lack of cleaners; traditional threshing exposes to pathogens 22;23. This loss can be mitigated by following Hermetic storage, fumigation (e.g., phosphine), mechanized drying/cleaning, proper packaging, and timely harvesting at physiological maturity. India's general PHL for spices 8-17% (approx.) per surveys.

Cumin (Cuminum cyminum) experiences post-harvest losses of approximately 10–20%, with 5–10% associated with shattering at harvest. Major causes include harvesting at immature or overripe stages, improper drying resulting in volatile-oil losses, and storage infestation by Tribolium spp 24,25.

Coriander (Coriandrum sativum) may incur 12–25% losses, including approximately 8–15% from handling and spillage. Umbel shattering, mould development under high humidity and carryover of Fusarium spp. are important causes, particularly when umbels are overripe 26 .

Fennel (Foeniculum vulgare) can experience 8–18% losses, with 5–10% attributed to threshing, mainly due to seed drop during manual beating and infestation by Callosobruchus beetles 27, 28

Fenugreek (Trigonella foenum-graecum) generally shows 10–15% losses, including approximately 5–8% during drying, primarily because of slow sun-drying, moisture-induced mould development and breakage during rough transportation 29, 30

Ajwain (Trachyspermum ammi) may experience 15–22% losses, while severe storage infestation under poor conditions can result in very high damage. Lasioderma serricorne, spillage and the use of inadequately protective gunny bags are major contributing factors.

Anise (Pimpinella anisum) may incur 10–20% losses, with microbial deterioration accounting for approximately 6–12% under high-moisture conditions; shattering during manual harvesting and condensation further contribute to deterioration 31, 32.

Caraway (Carum carvi) can show 8–16% losses, including approximately 4–8% weight loss, mainly due to inadequate drying and infestation by Tribolium castaneum. Celery (Apium graveolens) may experience 12–20% losses, with 7–10% associated with seed shattering caused by inappropriate umbel maturity, while fungal attack, including Erysiphe polygoni, can further reduce quality 33, 34.

Dill (Anethum graveolens) may incur 10–18% losses, with approximately 5–10% due to spillage during handling and transportation; rough handling and storage beetles are important causes 35.

Nigella (Nigella sativa) may experience 12–22% losses, including 6–12% during threshing, primarily because of seed breakage, high humidity, moisture-induced spoilage and inefficient manual processing. Overall, these losses demonstrate that timely harvesting, controlled drying, mechanized threshing, hygienic handling, appropriate packaging and scientifically managed storage are essential for reducing quantitative and qualitative deterioration in seed spices4,21.

Molecular approaches for enhancing the shelf life of seed spices

Molecular approaches provide opportunities to address these limitations at the genetic, cellular, and metabolic levels by modifying key biochemical pathways, enhancing endogenous antioxidant defense mechanisms and suppressing processes associated with post-harvest deterioration.

One important molecular strategy involves the genetic regulation of essential oil biosynthesis and stability. The commercial value of seed spices is largely determined by volatile organic compounds (VOCs), which are synthesized and stored in specialized secretory structures such as glandular trichomes and secretory canals 36. During storage, these volatile constituents can undergo auto-oxidation and enzymatic degradation, resulting in alterations in aroma and flavour profiles. Manipulation of the biosynthetic pathways responsible for terpene production may therefore contribute to improved retention of essential oils. In particular, the methylerythritol phosphate (MEP) and mevalonate (MVA) pathways play central roles in the biosynthesis of monoterpenes and sesquiterpenes 37. Upregulation of rate-limiting enzymes such as 1-deoxy-D-xylulose-5-phosphate synthase (DXS) in the MEP pathway and 3-hydroxy-3-methylglutaryl-CoA reductase (HMGR) in the MVA pathway can enhance the initial accumulation of essential oil constituents 38. In addition, suppression of enzymes involved in the degradation or oxidation of volatile compounds, including specific terpene oxidases, through RNA interference (RNAi) or other gene-silencing approaches could potentially reduce the loss of important aroma compounds and help maintain the characteristic volatile profile during extended storage.

Another major molecular target is the mitigation of lipid peroxidation and reactive oxygen species (ROS) accumulation. Seed spices contain membrane and storage lipids rich in unsaturated fatty acids, which are highly susceptible to oxidative deterioration during storage. Lipoxygenase (LOX) catalyses the oxygenation of polyunsaturated fatty acids to form lipid hydroperoxides, which can subsequently generate aldehydes, ketones, and other secondary oxidation products responsible for rancid or undesirable flavours 39. Consequently, suppression of specific LOX gene isoforms through gene knockdown or genome-editing approaches such as CRISPR/Cas9 could reduce oxidative lipid degradation and improve storage stability 40, 41. At the same time, enhancement of the endogenous antioxidant system provides another mechanism for limiting oxidative damage. Overexpression or enhanced expression of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) can facilitate the detoxification of superoxide radicals and hydrogen peroxide generated during seed maturation, drying, and storage. Strengthening these enzymatic antioxidant systems can help maintain membrane integrity and reduce oxidative deterioration, thereby contributing to improved seed quality and longevity 42 .

The manipulation of desiccation- and storage-protective proteins represents another promising molecular strategy for maintaining seed quality during prolonged storage. Seed drying imposes considerable cellular stress, and the loss of water can cause structural destabilization of proteins and membranes 43 . Late embryogenesis abundant (LEA) proteins play an important protective role during seed maturation and dehydration by stabilizing cellular proteins and membranes and preventing structural damage under low-water conditions. Therefore, the identification of favourable LEA alleles through marker-assisted selection (MAS), together with the potential enhancement of LEA gene expression through genetic engineering, may contribute to improved tolerance to desiccation and prolonged storage 44. Similarly, heat shock proteins (HSPs), particularly small heat shock proteins (sHSPs), function as molecular chaperones that prevent protein aggregation and assist in maintaining protein homeostasis under thermal and other abiotic stresses. Regulation of heat shock transcription factors (HSFs) and subsequent enhancement of sHSP accumulation may therefore improve the ability of seeds to withstand temperature fluctuations encountered during post-harvest handling and storage 45.

Hormonal regulation, particularly involving abscisic acid (ABA) and ethylene, also influences seed dormancy, metabolic activity, respiration, senescence, and storage longevity. ABA is a central regulator of seed maturation and dormancy, and appropriate maintenance of ABA signaling can help prevent premature germination and excessive metabolic activity. Molecular manipulation of key ABA biosynthetic genes, such as 9-cis-epoxycarotenoid dioxygenase (NCED), or modulation of ABA catabolism may enhance dormancy and reduce metabolic exhaustion during storage. However, such manipulation needs to be carefully regulated because excessive ABA accumulation may adversely affect germination performance after storage 46, 47. Ethylene signaling and biosynthesis are also associated with senescence and stress responses. Downregulation of key ethylene biosynthetic enzymes, particularly 1-aminocyclopropane-1-carboxylate synthase (ACS) and 1-aminocyclopropane-1-carboxylate oxidase (ACO), has been proposed as a strategy to reduce ethylene production and potentially delay senescence-related deterioration and susceptibility to microbial infection 48.

Recent advances in CRISPR/Cas9 genome editing, base editing, and prime editing provide additional opportunities for the precise manipulation of genes associated with post-harvest quality and storage longevity. Genome editing enables targeted modification of endogenous genes and 49 in some applications, can generate plants without stable incorporation of foreign DNA, which may offer advantages for the development and regulatory acceptance of improved culinary crops. Targeted loss-of-function mutations in susceptibility (S) genes could potentially enhance resistance to post-harvest fungal pathogens, including Aspergillus and Fusarium species, thereby reducing microbial deterioration. In addition, promoter editing can be employed to fine-tune the expression of endogenous antioxidant and stress-responsive genes rather than simply switching them on or off. CRISPR-based base and prime editing technologies may therefore enable precise modification of regulatory sequences and the development of desirable expression patterns during seed maturation, drying, and storage 50.

Collectively, these molecular approaches demonstrate that improvement of seed-spice shelf life can be addressed through coordinated manipulation of essential oil biosynthesis and stability, lipid oxidation, antioxidant defence, desiccation tolerance, molecular chaperones, hormonal signaling, and pathogen susceptibility. Integrating conventional breeding and marker-assisted selection with transcriptomics, metabolomics, functional genomics, RNA interference, and precision genome-editing technologies could facilitate the development of seed-spice cultivars with enhanced storage stability while retaining their characteristic aroma, flavor, bioactive compounds, and germination potential. Nevertheless, the application of these approaches to spices requires careful consideration of species-specific biosynthetic pathways, the complexity of essential-oil composition, genotype × environment interactions, and regulatory and consumer acceptance before molecularly improved cultivars can be effectively translated into commercial production.

Table 1 Molecular strategies for enhancing the shelf life of seed spices

Molecular Strategy	Key Target Genes/Enzymes	Primary Mechanism	Outcome on Shelf Life	References
Lipid Stabilization	LOX (Lipoxygenase) knockdown	Inhibits polyunsaturated fatty acid cleavage	Prevents rancidity and off-flavors	51, 52
ROS Clearance	Overexpression of SOD, CAT, APX	Scavenges free radicals during storage	Maintains cell membrane integrity	53,54
Desiccation Protection	LEA and sHSP upregulation	Protects protein structures in low-water states	Preserves seed vigor and viability	55
Ethylene Control	ACS and ACO knockouts	Blocks post-harvest ethylene signaling	Delays senescence and microbial decay	56
Volatile Retention	Fine-tuning DXS / TPS pathways	Optimizes terpene and essential oil yield	Retains aroma and essential oil potency	48

Future prospects

Future reduction of post-harvest losses in seed spices will depend on the integration of precision processing, smart storage, sustainable preservation and value-chain interventions. Solar-assisted, hybrid and controlled drying systems can improve moisture uniformity while reducing thermal damage to essential oils and other bioactive constituents. Emerging non-thermal technologies, including ultrasound, pulsed electric fields and other low-energy decontamination approaches, warrant further validation for spice-specific applications. Smart storage integrating hermetic systems, sensors and IoT-based monitoring can provide real-time information on moisture, temperature and storage conditions, thereby enabling early intervention against quality deterioration. Hermetic storage has demonstrated potential for limiting insect-mediated storage losses when appropriate drying conditions are maintained 57 ; 20,.

Sustainable preservation strategies, including botanical antimicrobials, essential oils, biodegradable films and edible coatings, may reduce dependence on synthetic chemicals. Value addition through powders, oleoresins and essential oils can further reduce storage and marketing risks while increasing product value. Strengthening rural drying, storage and processing infrastructure, together with farmer training and collective action through FPOs, will be essential for technology adoption. FAO emphasizes that inadequate infrastructure, packaging and technical capacity remain major constraints to post-harvest loss reduction. Climate-resilient processing and storage systems should therefore be prioritized to maintain seed-spice quality under increasing temperature and humidity variability58, 59.

CONCLUSION

Reduction of post-harvest losses in seed spices requires an integrated approach combining scientific processing, advanced technologies, sustainable practices and effective value-chain management. Optimization of harvesting, drying, threshing, cleaning, grading, packaging and storage is essential for maintaining essential oils, bioactive compounds, sensory quality and microbial safety. Emerging technologies such as solar and mechanical drying, hermetic storage, modified-atmosphere packaging, IoT-based monitoring, artificial intelligence and digital traceability can improve process efficiency and enable real-time quality management. Molecular approaches further provide opportunities to identify and utilize genotypes with enhanced antioxidant capacity, resistance to storage pests and improved biochemical stability.

Sustainability should remain central to future post-harvest systems through the adoption of biodegradable packaging, botanical preservatives, energy-efficient processing and reduced chemical inputs. Strengthening rural infrastructure, decentralized processing facilities, scientific storage systems and farmer training is equally important for translating technological advances into practical benefits. Collective approaches through Farmer Producer Organizations and cooperatives can improve access to processing technologies and strengthen market linkages. Ultimately, integration of post-harvest technology with molecular science, digital tools and farmer-centered interventions can substantially reduce quantitative and qualitative losses, extend shelf life, improve farmer returns and enhance the safety, sustainability and global competitiveness of the seed-spice industry.

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