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Perspectives on Post-Harvest and Storage Technologies for Legume Crops: A Review

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Abstract

Legume crops are among the most important sources of plant-based protein, dietary fiber and micronutrients worldwide. However, post-harvest deterioration caused by moisture, pest infestation, microbial contamination and inadequate storage remains a major challenge, particularly in tropical and subtropical regions. This review presents a comprehensive synthesis of current and emerging post-harvest and storage technologies designed to preserve the quality and extend the shelf life of these crops. Traditional practices are evaluated alongside advanced systems, including hermetic storage, modified and controlled atmosphere storage (MA/CA), improved drying techniques and cold storage. Hermetic storage technologies such as triple-layer PICS bags and airtight silos have proven highly effective in reducing insect and fungal damage, while MA/CA storage suppresses respiration and pest activity through altered gas composition. Improved drying systems, especially hybrid solar-biomass and mechanical dryers, enhance moisture control and reduce contamination risks, whereas cold storage maintains seed viability and nutritional quality under controlled temperatures. The review further explores innovative technologies such as ozone treatment, cold plasma, irradiation and nanotechnology-based smart packaging, which offer chemical-free, sustainable alternatives for legume preservation. Biological and botanical pest control methods and integrated post-harvest systems are highlighted as eco-friendly strategies for reducing reliance on synthetic pesticides. Future perspectives emphasize the importance of policy and institutional support, research innovation and the integration of digital technologies (IoT, AI and biosensors) for real-time monitoring and decision-making. Addressing challenges related to cost, accessibility, and technical capacity—particularly in developing countries—remains critical for large-scale adoption. Overall, the review underscores that sustainable post-harvest management of legumes requires a multidimensional approach that combines technological advancement, environmental stewardship and inclusive policy frameworks to enhance global food security and resilience.

Keywords: *Legumes, Postharvest, modified atmosphere, control atmosphere, shelf life.*

1. Introduction

Legume crops including common bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*), chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), pigeon pea (*Cajanus cajan*) and mung bean (*Vigna radiata*) play vital roles in global food and nutrition security [47]. They are rich sources of protein, dietary fiber, essential minerals and bioactive compounds that complement cereal-based diets [34]. Moreover, legumes contribute to sustainable agricultural systems through biological nitrogen fixation, improving soil fertility and reducing the dependence on synthetic fertilizers [31][21][25]. Despite these benefits, legume production systems, especially in low- and middle-income countries, are constrained by substantial post-harvest losses (PHL) resulting from poor drying, inadequate storage, insect pest infestation and adverse environmental conditions [1].

Post-harvest and storage losses of legumes are often underestimated but can reach 20–30% of production, depending on crop type and region [44]. For instance, a recent study in Uganda reported that smallholder bean producers lost up to 22% of total harvest value due to inadequate drying and poor storage structures, with 74% of stored beans exceeding the recommended moisture content of 13% [40]. These losses not only reduce the quantity available for consumption but also deteriorate nutritional quality, seed viability and market value [27]. In addition, the physiological and biochemical characteristics of legumes, such as their high protein and oil content make them more susceptible to deterioration during storage than cereals [50]. The major causes of deterioration during storage include bruchid beetle infestation (*Callosobruchus spp*.), high grain moisture, elevated temperature and humidity and poor handling practices [39].

Temperature and moisture interactions accelerate the development of the "hard-to-cook" (HTC) defect, protein denaturation, and loss of seed viability [57]. A recent controlled study on faba and adzuki beans demonstrated that storage under high temperature (40 °C) and humidity (80% RH) resulted in reduced starch gelatinization, lower protein solubility and significant declines in sensory quality within six months [29]. Similar findings have been reported for chickpea and lentil, emphasizing that storage conditions strongly influence seed structure, nutrient retention, and cooking characteristics [46].

Emerging technologies are increasingly being applied to mitigate these post-harvest challenges. Hermetic storage systems, which restrict oxygen exchange and elevate carbon dioxide levels, have proven particularly effective in controlling insect activity and maintaining quality [6]. Studies show that hermetic bags can eliminate up to 100% of bruchid infestation and prevent weight loss compared to conventional woven polypropylene bags [35]. Similarly, hybrid solar dryers and mechanical dryers are being introduced to reduce drying time and achieve safe moisture content before storage [48]. Modified atmosphere (MA) and controlled atmosphere (CA) systems are also gaining attention for high-value legume seeds, as they can preserve germination and nutrient stability [48].

Furthermore, the integration of sensor-based and Internet of Things (IoT) systems into legume storage enables real-time monitoring of moisture, temperature, and pest activity, thereby improving decision-making [26]. Despite promising evidence, the adoption of these post-harvest and storage technologies remains limited in smallholder contexts. Factors such as initial investment cost, lack of awareness, and inadequate access to reliable drying and storage equipment hinder widespread uptake [1]. A recent scoping review of post-harvest interventions in Sub-Saharan Africa and South Asia found that 71% of loss-reduction efforts focused on storage, yet only about 8% targeted legume crops [15]. This disparity suggests a need for more legume-specific research, extension and technology dissemination programs. In this context, the present review aims to provide a comprehensive analysis of recent advances and perspectives in post-harvest and storage technologies for legume crops. Specifically, it synthesizes current evidence (2020–2025) on (i) major causes of post-harvest losses, (ii) technological innovations for drying and storage, (iii) effectiveness, cost-benefit, and sustainability of these technologies, and (iv) adoption barriers and research gaps. The review emphasizes both the scientific and practical implications for improving legume storage in developing regions, highlighting technologies that can enhance food quality, safety, and economic returns along the legume value chain [15].

2. Key Causes of Post-Harvest Deterioration in Legumes

Post-harvest deterioration in legume crops results from a combination of biotic and abiotic factors that interact during harvesting, drying, handling and storage. The magnitude of deterioration varies with crop type, climatic condition, storage environment and pre-harvest management. The principal causes include insect infestation, microbial contamination, moisture and temperature fluctuations, physiological seed aging and mechanical damage. These factors collectively affect seed viability, cooking quality and market value.

2.1 Insect Infestation

Insect damage is the most critical post-harvest constraint affecting stored legumes. The bruchid beetles *(Callosobruchus maculatus, C. chinensis, Acanthoscelides obtectus)* are the most destructive pests, capable of causing 30–70% grain damage within three to six months under tropical conditions [6]. Infested seeds suffer weight loss, reduced germination, and increased susceptibility to fungal infection. The bruchid lifecycle occurs entirely inside the seed, making control difficult once infestation begins [7][9]. The female lays eggs on the seed surface, larvae penetrate the cotyledon and the adults emerge through exit holes, further facilitating re-infestation. Research demonstrates that temperature and moisture significantly influence insect activity.

According to [8], bruchid population growth in cowpea doubles when temperature increases from 25 °C to 35 °C and seed moisture content exceeds 13%. Such conditions are common in sub-Saharan Africa and South Asia, where traditional storage lacks hermetic sealing. Hermetic storage solutions like Purdue Improved Crop Storage (PICS) bags have reduced insect-related losses by up to 95% compared with polypropylene bags [44][41].

2.2 Fungal and Microbial Contamination

Microbial infection is another key contributor to post-harvest deterioration. Fungi such as Aspergillus flavus, Penicillium spp., and Fusarium spp. readily colonize poorly dried seeds, especially when relative humidity exceeds 70% [10][36][55]. These fungi can lead not only to discoloration and rancidity but also to mycotoxin contamination, notably aflatoxins, which are carcinogenic and pose major food safety risks. Studies in Nigeria and Ethiopia have shown aflatoxin concentrations in stored cowpea and groundnut exceeding the permissible limits ($\geqslant$ 20 µg kg^{-1}) when moisture is above 12% and ambient temperatures are over 30 °C [3]. Moisture control and aeration are essential to preventing fungal proliferation. Recent advancements in solar-assisted dryers and moisture-sensing smart bins demonstrate significant potential to reduce microbial spoilage by maintaining equilibrium relative humidity (ERH) below 65% [54]. However, their high initial cost and limited access in smallholder contexts remain major barriers to adoption.

2.3 Moisture Content and Temperature Fluctuations

Moisture is a dominant determinant of legume storability. When seeds are stored above their safe moisture content (typically 10–12%), respiration accelerates, increasing heat generation, carbon dioxide accumulation, and seed deterioration [45][52][56]. Temperature and humidity jointly influence the equilibrium moisture content of stored legumes, and failure to maintain stable environmental conditions accelerates biochemical degradation. For instance, high temperatures enhance lipid oxidation and non-enzymatic browning reactions, leading to the "hard-to-cook" defect [52]. In tropical regions, unprotected storage environments expose grains to fluctuating daily temperatures, which cause condensation inside bags, creating micro-zones favorable for microbial and insect activity [26]. Modern storage systems, such as hermetic silos and multilayer polymer bags, address these issues by limiting oxygen diffusion and moisture exchange, though widespread dissemination remains limited [6].

2.4 Physiological Seed Aging

Physiological deterioration caused by prolonged storage and unfavorable environmental conditions results in reduced germination and seed vigor. During aging, the accumulation of reactive oxygen species (ROS) leads to lipid peroxidation, protein denaturation and nucleic acid degradation [50]. Storage temperature above 25 °C and moisture content above 12% accelerate these oxidative processes. Seed respiration during storage also leads to carbon dioxide accumulation and depletion of energy reserves, further compromising viability. Recent metabolomic analyses have revealed that loss of legume seed viability is associated with reduced activities of antioxidant enzymes such as superoxide dismutase (SOD) and (CAT) catalase [57]. Thus, maintaining low storage temperatures and relative humidity is crucial to delaying metabolic deterioration. Research into bio-based antioxidants and nano-coatings is emerging as a potential strategy to extend seed shelf life [45].

2.5 Combined Effects and Climate Variability

The combined impact of these factors is often amplified by climate variability, which alters temperature and humidity patterns, extending insect breeding cycles and increasing fungal incidence [50]. A warming trend of 1–2 °C can reduce safe storage duration of cowpea by 25–30%, even under sealed conditions [50]. Therefore, integrated post-harvest management system in stored legumes involves combining proper drying, hermetic storage, pest control and close monitoring of the climatic and environment factors such as temperature and relative humidity to mitigate deterioration under changing climatic conditions.

3.1 Hermetic storage (bags, silos)

Hermetic storage — implemented most commonly as multi-layer hermetic bags and sealed silos, creates a modified atmosphere around stored legumes by restricting gas exchange between the commodity and the external environment. Respiration by seeds and any resident insects consumes oxygen and raises carbon dioxide concentrations, producing an environment that is lethal or inhibitory to many storage pests and suppressive to aerobic fungal growth. Because this approach achieves pest control and quality preservation without routine chemical fumigation, it has become an attractive, lower-risk option for smallholder and larger-scale legume storage systems [8]. Evidence from experimental and field studies indicates that hermetic bags (e.g., the Purdue Improved Crop Storage — PICS — design and other triple-layer bags) substantially reduce insect populations and preserve mass and quality attributes of legumes during storage. Trials with cowpea and other pulses show markedly lower insect survival and reduced percentage weight loss in hermetic bags versus conventional woven polypropylene sacks over storage periods of several months [8].

In addition to physical protection against pests, hermetic conditions can help maintain seed viability and limit deterioration of nutritional components; studies on common bean varieties stored in PICS bags reported better retention of key nutritional and anti-nutrient profiles compared with non-hermetic storage [32]. Hermetic silos and silo-bag systems apply the same airtight principle at larger scales: sealed metal or plastic silos can store communal or commercial volumes, while field-deployed silo bags are useful for bulk, temporary storage. These larger formats are appropriate where economies of scale justify higher capital cost and where infrastructure and handling systems are available. By contrast, hermetic bags are comparatively low-cost and highly adoptable by smallholder farmers because they require little infrastructure and can be deployed at the farm level [8]. Despite strong evidence of efficacy, hermetic storage is not a panacea. The system's protective effect depends critically on pre-storage drying; seeds or pods must be brought to safe moisture contents (commonly ⩽ 10–12% for many legumes) because high internal moisture under hermetic conditions can promote anaerobic spoilage, fermentation or mycotoxin production [26]. Physical integrity of the container is also essential: punctures, poor seals, or handling damage allow oxygen ingress and can rapidly undermine the hermetic atmosphere and its benefits [26].

Finally, adoption at scale requires attention to cost-benefit tradeoffs — hermetic bags are low-cost for small lots, whereas silos demand higher investment but are suitable for cooperative or commercial storage [8]. Hermetic storage (bags and silos) represents a robust, chemical-free approach to reducing post-harvest losses and preserving quality in legumes. When combined with adequate drying and proper handling, hermetic technologies can substantially reduce entomological and physiological deterioration, support seed viability and enable farmers and traders to store legumes safely until favorable market or processing conditions arise.

3.2 Modified/Controlled Atmosphere (MA/CA) Storage

Modified Atmosphere (MA) and Controlled Atmosphere (CA) storage technologies are among the most advanced post-harvest strategies for maintaining the quality and safety of legumes during medium- to long-term storage. These systems work by adjusting and maintaining the composition of gases—mainly oxygen (O_2), carbon dioxide (CO_2), and nitrogen (N_2)—within the storage environment. The objective is to reduce oxidative reactions, respiration and insect or microbial activity, thereby extending the shelf life of stored commodities [11][38]. In MA storage, the atmosphere within the storage container is modified initially and allowed to change passively due to commodity respiration, whereas CA storage actively monitors and regulates gas composition throughout the storage period. For legumes such as cowpea, lentil, and chickpea, maintaining low O_2 (<2–5%) and elevated CO_2 (up to 60%) levels effectively suppresses insect pests such as *Callosobruchus maculatus* and *Acanthoscelides obtectus,* while slowing seed respiration and delaying deterioration [22].

Recent studies have demonstrated that high-CO_2 or low-O_2 atmospheres can completely control bruchid populations within 5–10 days without chemical insecticides, highlighting MA/CA storage as an environmentally safe alternative to fumigation [18]. In chickpeas and lentils stored under a 60% CO_2 atmosphere at 25 °C, significant reductions in seed damage and insect development were reported compared with ambient air storage [22]. Additionally, the modified atmosphere helped retain protein integrity, color and germination viability for several months. Besides pest control, MA/CA storage can maintain seed vigor and limit lipid oxidation and enzymatic browning, thus preserving sensory and nutritional attributes [11]. However, the technology requires precise gas monitoring and airtight infrastructure, which can increase operational costs. As a result, MA/CA storage is more commonly adopted in industrial or commercial storage facilities than among smallholder farmers, particularly in low- and middle-income regions. Integration of MA/CA systems with other storage strategies such as refrigeration, hermetic packaging or natural CO_2 generation through biological means offers further potential for sustainable post-harvest management of legumes [39].

The growing interest in bio-generated modified atmospheres (e.g., using seed respiration or CO_2-producing pads) demonstrates a trend toward energy-efficient and eco-friendly adaptations of CA storage. MA/CA storage technologies represent a scientifically validated, chemical-free method to control storage pests, maintain seed quality, and reduce losses in legume supply chains. While their cost and complexity may limit small-scale adoption, continued development of low-cost systems and bio-based atmosphere modifiers could expand their accessibility and impact in developing regions.

3.3 Improved Drying Systems

Drying is one of the most critical post-harvest operations in legume processing because legumes with high moisture content are prone to fungal growth, insect infestation, and quality deterioration during storage [30]. Traditional sun-drying methods, although inexpensive, are highly dependent on weather conditions and often lead to uneven drying, contamination by dust, and loss due to rodents and birds [50]. To overcome these limitations, improved drying systems—such as solar dryers, hybrid solar–biomass dryers, and mechanical dryers have been increasingly developed and adopted in recent years [1]. Solar drying technologies represent a sustainable solution for smallholder farmers because they utilize renewable energy and minimize post-harvest losses. Indirect solar dryers, for instance, protect grains from direct exposure to sunlight, ensuring uniform heat distribution and preservation of seed viability [19].

Mechanical drying, often using batch or continuous-flow dryers, provides greater control over air temperature and humidity, leading to improved drying efficiency and product quality. Hybrid dryers that combine solar energy with auxiliary heat sources (e.g., LPG or biomass) offer consistent performance even under cloudy conditions [33]. Such systems significantly reduce drying time and microbial contamination compared to traditional methods [31]. However, high operational and energy costs limit their adoption among smallholder farmers in developing regions. To address this, recent innovations have focused on energy-efficient dryers equipped with heat recovery systems and smart sensors for real-time moisture monitoring [1]. The integration of improved drying technologies with hermetic storage can further enhance the shelf life and quality of legumes by maintaining low moisture levels throughout the supply chain [8]. Future research should prioritize cost-effective and decentralized drying systems adaptable to different agro-ecological zones and legume species.

3.4 Cold Storage Systems

Cold storage systems play a vital role in maintaining the post-harvest quality of legume crops by slowing metabolic activities, insect development, and microbial growth [27]. Although legumes are relatively less perishable than fruits and vegetables, they are still vulnerable to deterioration when stored under warm and humid conditions, especially in tropical regions [47]. Low-temperature storage has been shown to preserve seed viability, maintain nutritional composition, and prevent rancidity and discoloration in pulses such as cowpea, chickpea, and lentils [12]. Cold storage works by reducing the respiration rate of the stored seeds, thereby extending their shelf life and reducing the risk of insect infestation [31]. Insects such as *Callosobruchus maculatus* and *Bruchidius atrolineatus*, which are common pests of stored legumes, show limited reproductive activity below 15 °C, making cold environments an effective non-chemical control method [54].

Moreover, cold storage also contributes to the maintenance of germination potential and protein integrity, which are critical for both seed preservation and food quality [27]. Recent advances have focused on the use of energy-efficient cold rooms and solar-powered refrigeration systems to make cold storage feasible in rural and off-grid areas. These innovations aim to reduce dependence on fossil fuels and mitigate high operational costs associated with conventional cold stores [28]. Furthermore, integrated cold chain systems, combining cold storage with hermetic or modified atmosphere packaging, have demonstrated improved preservation of legumes over extended periods [30]. Despite its advantages, the high capital and energy requirements of cold storage remain major barriers to widespread adoption among smallholder farmers in developing countries [41]. Therefore, there is a growing research emphasis on low-cost evaporative cooling systems and phase-change material (PCM)-based cooling units that can provide moderate temperature control without continuous power supply [20]. Such systems not only enhance food security but also align with global sustainability and carbon neutrality goals.

3.5 Emerging Technologies for Post-Harvest Legume Preservation

In recent years, emerging technologies have gained significant attention as alternatives or complements to conventional post-harvest methods for maintaining the quality and safety of legume crops. These innovative approaches such as ozone treatment, cold plasma, irradiation, nanotechnology-based packaging and smart monitoring systems, aim to reduce post-harvest losses, minimize chemical use and extend storage life while maintaining nutritional integrity [27][14].

Ozone treatment is an environmentally friendly technology used to control microbial growth and insect infestation in stored legumes. Ozone acts as a strong oxidizing agent capable of degrading mycotoxins, spores and pathogens without leaving chemical residues [54]. Studies have shown that exposure of stored pulses to low ozone concentrations effectively inactivates storage pests like *Callosobruchus maculatus* and reduces fungal contamination while preserving seed viability [9].

Cold plasma technology is another promising approach, offering rapid surface decontamination of legume seeds through the generation of reactive oxygen and nitrogen species. This non-thermal process can significantly reduce microbial load and insect eggs without affecting germination potential or nutritional composition [46]. Moreover, plasma treatment can modify the seed surface to enhance coating or impregnation with protective agents, making it suitable for integrated pest management systems [53].

Food irradiation: Gamma rays, X-rays or electron beams have been successfully applied to sterilize legumes and control post-harvest pests.

Irradiation at doses between 0.25–1.0 kGy effectively eliminates bruchid beetles and prevents mold growth during extended storage [43]. The technology also reduces dependence on chemical fumigants and meets international quarantine standards, making it valuable for global trade [16].

Nanotechnology-enabled packaging systems represent a modern trend in legume preservation. Nanocomposite films infused with silver, zinc oxide, or chitosan nanoparticles provide antimicrobial properties and enhanced barrier performance against oxygen and moisture [58]. Furthermore, the development of intelligent packaging with nano-sensors enables real-time monitoring of temperature, humidity and gas composition inside storage units [27]. Such innovations ensure quality tracking throughout the storage and distribution chain.

The integration of Internet of Things (IoT) and machine learning for post-harvest management has opened new frontiers in data-driven decision-making. These technologies facilitate continuous monitoring of environmental conditions, early detection of spoilage, and optimization of energy use in storage facilities [2]. Collectively, these emerging approaches offer sustainable and efficient pathways to improve legume preservation, enhance food safety, and minimize post-harvest losses.

3.6 Biological and Botanical Pest Control Methods

The use of biological and botanical control agents has gained increasing attention as an eco-friendly alternative to synthetic chemical pesticides for protecting stored legumes. These approaches harness the pesticidal properties of naturally occurring compounds, plant extracts and beneficial microorganisms to control bruchid beetles and fungal pathogens that commonly infest stored pulses [50]. Botanical insecticides derived from *Azadirachta indica* (neem), *Ocimum gratissimum* (African basil), and *Cymbopogon citratus* (lemon grass) have demonstrated strong insecticidal and repellent activity against *Callosobruchus maculatus* and *Acanthoscelides obtectus* in cowpea and chickpea storage [17][4].

The mechanism of action of these botanicals involves interference with insect feeding, respiration, and reproduction, while leaving minimal residue on stored produce. Neem seed oil, in particular, has shown high efficacy at 5–10 mL/kg of cowpea grains, causing 100% mortality of adult bruchids within seven days [4]. Similarly, essential oils from *Eucalyptus globulus* and *Mentha piperita* exhibit fumigant toxicity and ovicidal effects, making them potential biofumigants for legume storage [24]. Biological control using beneficial organisms such as *Beauveria bassiana*, *Metarhizium anisopliae,* and *Trichoderma harzianum* has also shown promise in suppressing insect populations and mycotoxigenic fungi during storage [28]. The spores of these entomopathogenic fungi infect and kill insects by penetrating the cuticle and proliferating internally. In addition, microbial antagonists like *Lactobacillus plantarum* and Bacillus *subtilis* have been explored for inhibiting fungal growth and aflatoxin production in stored legumes [42]. While biological and botanical agents offer sustainability and safety benefits, challenges remain regarding their standardization, formulation stability and shelf-life. Future research should focus on optimizing application rates, combining different biocontrol agents, and developing formulations compatible with existing storage systems such as hermetic or modified atmosphere environments.

3.7 Integration of Post-Harvest Systems

An integrated post-harvest management (IPHM) approach combines multiple complementary technologies—such as improved drying, hermetic storage and modified atmosphere systems—to enhance legume preservation, reduce losses and ensure long-term quality stability [39]. The integration of these technologies addresses multiple deterioration factors simultaneously, including moisture, insect activity, and microbial contamination, while promoting energy and cost efficiency [5]. For instance, legumes that undergo solar or hybrid drying to reach safe moisture levels (<12%) before hermetic or MA/CA storage show significantly improved shelf life and reduced pest incidence. Similarly, combining biological pest control with hermetic packaging has been reported to enhance pest suppression without compromising seed viability [4]. Such integrated systems are also adaptable to different production scales, from smallholder household storage to commercial warehouses. The success of integrated systems depends on proper sequencing and compatibility between technologies. For example, dried beans stored in triple-layer PICS bags under modified atmosphere conditions experience synergistic effects that inhibit both insects and fungi [39]. Moreover, the adoption of smart digital monitoring systems such as IoT-based temperature and humidity sensors within these integrated setups enables real-time quality assessment, early spoilage detection, and optimized resource use [2].

However, widespread implementation of integrated post-harvest systems requires coordinated investment, training and policy support to ensure that smallholder farmers can access and manage these technologies effectively. Future directions should emphasize participatory design, renewable energy integration, and the development of decision-support models for optimizing technology combinations according to local environmental and socioeconomic conditions.

4.0 Future Prospects and Challenges in Post-Harvest Management of Legume Crops

The global demand for legumes continues to rise due to their nutritional, economic, and environmental importance. However, efficient post-harvest management remains a major challenge, particularly in developing countries where high temperatures, humidity, and limited infrastructure accelerate deterioration and losses [1]. While significant progress has been made in developing improved storage, drying, and preservation technologies, several issues hinder large-scale adoption and sustainability.

One of the major challenges is the limited accessibility and affordability of advanced technologies such as hermetic silos, cold storage, and plasma or ozone treatment among smallholder farmers.

The initial capital investment and energy costs of these systems restrict their use to commercial-scale operations. Therefore, future strategies must focus on cost-effective, scalable, and decentralized systems suitable for rural settings [28]. Integrating renewable energy sources such as solar and biomass into drying and storage systems could substantially reduce operational costs while promoting environmental sustainability [5]. Another emerging concern involves climate change and its effects on post-harvest stability. Increasing temperature variability and pest proliferation due to global warming are expected to intensify storage challenges for legumes. Climate-resilient storage technologies such as adaptive hermetic systems and phase-change cooling materials should therefore be prioritized in future research and policy frameworks [20]. Furthermore, the adoption of digital and smart technologies, including Internet of Things (IoT), artificial intelligence (AI), and blockchain holds promise for real-time monitoring and management of post-harvest systems [2]. These technologies can predict spoilage, optimize temperature and humidity control, and trace the quality of legumes along the supply chain [26]. However, the implementation of such systems in low-resource contexts requires technical training, investment in data infrastructure, and strong institutional support. Policy and capacity building also play a critical role in ensuring the sustainability of post-harvest interventions. The lack of coordinated extension services, weak farmer education programs, and insufficient post-harvest research funding remain obstacles to effective technology dissemination [12]. Governments and international development agencies must therefore strengthen research-extension linkages and promote farmer cooperatives to facilitate the sharing of post-harvest innovations. Lastly, environmental sustainability should be embedded in all post-harvest technology development efforts. The transition toward eco-friendly materials for packaging, reduced reliance on synthetic fumigants and circular waste management practices aligns with the global agenda for sustainable food systems [16].

Future studies should also evaluate the life-cycle impacts of new technologies to ensure that environmental benefits are achieved alongside improved food security. Advancing post-harvest and storage technologies for legume crops requires a multi-pronged approach that integrates technological innovation, sustainability principles, and inclusive capacity-building. Collaboration between researchers, policymakers, and private sectors will be essential to unlock the full potential of legumes in supporting global nutrition and sustainable agriculture.

4.1 Policy and Institutional Support

Effective post-harvest management of legume crops depends not only on technological advancements but also on supportive policy and institutional frameworks that promote adoption, capacity building, and knowledge transfer. In many developing countries, post-harvest interventions are fragmented, poorly coordinated, and inadequately supported by national agricultural policies. Strengthening institutional linkages among government agencies, research institutions, and private sector actors is essential to bridge the gap between technology development and field-level application. National post-harvest strategies should prioritize the creation of legume storage and processing infrastructure, facilitate access to credit for smallholder farmers, and incentivize the adoption of climate-smart and energy-efficient technologies [1]. The establishment of agro-based cooperatives can enable farmers to pool resources for collective investment in technologies such as hermetic silos and solar dryers, thereby reducing individual costs [28]. Moreover, policy harmonization across regional trade blocs can enhance the marketing and export of quality legumes by enforcing consistent post-harvest handling standards. Institutions such as the FAO, IITA, and national agricultural research systems (NARS) have a central role in promoting capacity development, disseminating post-harvest innovations, and coordinating multi-stakeholder partnerships. Gender inclusion and youth participation should also be mainstreamed into these policies to ensure equitable access to post-harvest technologies [16]. Finally, long-term policy commitment to extension services and technical training programs is vital to empower farmers and technicians with practical knowledge of improved storage and preservation systems. Public–private partnerships (PPPs) should be encouraged to accelerate technology diffusion and ensure sustainability beyond donor-driven projects.

4.2 Research and Innovation Priorities

Future research on legume post-harvest management must focus on developing sustainable, cost-effective, and adaptable technologies that address emerging challenges such as climate change, pest resistance, and resource limitations. Priority should be given to climate-resilient post-harvest systems that maintain performance under fluctuating temperature and humidity conditions [20]. This includes developing hybrid technologies that integrate renewable energy sources with conventional drying, storage, and packaging systems [20]. Advances in nanotechnology, smart packaging, and biosensors provide opportunities for real-time monitoring of legume quality and storage environments. Research should aim to enhance the affordability and scalability of these systems, particularly for smallholder farmers in low-income regions [28]. The exploration of bio-based materials for packaging and coating can also contribute to sustainability by reducing plastic waste and improving biodegradability. Another key research priority lies in microbial and biochemical preservation, including the study of natural antifungal and antioxidant compounds to reduce mycotoxin risks during storage [42]. Multidisciplinary collaboration between food technologists, engineers, microbiologists, and data scientists will be necessary to create integrated models that optimize post-harvest processes across different legume varieties and production environments [2]. In addition, socio-economic and behavioral studies should evaluate farmer perceptions, adoption barriers, and incentives to promote inclusive dissemination of technologies. Integrating digital innovation with community-based extension models will ensure equitable access and knowledge sharing among legume producers.

5. Conclusion

Post-harvest and storage technologies play a pivotal role in preserving the quality, safety, and nutritional value of legume crops commodities that are central to food and nutrition security worldwide. Despite their resilience compared to other agricultural products, legumes are still vulnerable to post-harvest deterioration caused by improper drying, pest infestation, and microbial contamination under tropical and subtropical conditions.

This review highlighted that a range of innovative and improved storage and preservation techniques such as hermetic storage, modified atmosphere systems, improved drying technologies, and cold storage have significantly reduced post-harvest losses and improved storage stability. Emerging technologies, including ozone and plasma treatment, irradiation, and nanotechnology-based intelligent packaging, represent promising frontiers for sustainable post-harvest management. These methods not only enhance microbial and pest control but also minimize chemical inputs, aligning with global efforts toward safer and more environmentally friendly food supply systems.

Moreover, integrating digital technologies such as IoT, AI, and smart sensors into legume storage and drying operations, have the potential to optimize environmental control, monitor quality in real time, and strengthen traceability throughout the supply chain. However, challenges persist particularly in developing countries, where the adoption of modern storage systems is constrained by high costs, limited technical know-how, and inadequate infrastructures. Addressing these gaps, require both capacity building, sharing technology between farmers globally, and policy frameworks that support innovation among the developing countries. Additionally, the development of energy-efficient and climate-resilient storage systems, powered by renewable resources is essential to ensure sustainability and adaptability under changing climatic conditions. Future research should prioritize the integration of low-cost technologies, eco-friendly materials, and data-driven decision tools that can improve legume quality while reducing post-harvest losses.

Collaborative efforts among researchers, policymakers, and industry stakeholders will be critical to scaling up these innovations and achieving the dual goals of food security and environmental sustainability.

The continuous evolution of post-harvest and storage technologies offers a promising path toward safeguarding legume crops, improving farmer livelihoods, and supporting global nutrition and sustainability agendas. The future of legume post-harvest management lies in merging technological innovation with inclusive and sustainable practices to build resilient food systems capable of meeting the demands of a growing population.

References

1. Abass, A. B., Ndunguru, G., Mamiro, P., Alenkhe, B., Mlingi, N., & Bekunda, M. (2020). Post-harvest food losses in a maize-based farming system of semi-arid savannah area of Tanzania. *Agriculture & Food Security, 9*(1), 1–12.
2. Abebe, G., Tadesse, A., & Mekonnen, D. (2024). Application of Internet of Things and machine learning for smart post-harvest management in grain storage systems. *Computers and Electronics in Agriculture, 221*, 109772.
3. Adebayo, A. R., Olalekan, A., & Musa, S. Y. (2022). Storage pests and mitigation strategies in legume grains: A mini-review. *Journal of Stored Products Research*, 97, 102049.
4. Adugna, D., Taye, M., & Lemi, T. (2023). Insecticidal efficacy of neem (*Azadirachta indica*) and basil *(Ocimum gratissimum*) oils against *Callosobruchus maculatus* in stored cowpea. *Journal of Stored Products Research,* 100, 102020.
5. Bala, B. K., Mondol, M. R. A., & Rahman, M. S. (2022). Solar drying technology: Potentials and challenges for agricultural products in developing countries. *Renewable and Sustainable Energy* Reviews, 160, 112309.
6. Baoua, I. B., Amadou, L., Ousmane, B., & Murdock, L. L. (2021). Performance of hermetic storage bags for cowpea preservation under tropical conditions. *Journal of Stored Products Research, 94*, 101858.
7. Baskin, J. M., & Baskin, C. C. (2025). Physical dormancy-break by predispersal insect seed predators and a discussion of insect x seed (bitrophic) interactions on population growth of legumes. *Planta*, *262*(2), 31.
8. Bawa, H. Y. D., Baoua, I. B., Rabé, M. M., & Baributsa, D. (2025). Hermetic Bags Effectively Manage Emerging and Common Pests of Stored Cowpeas in Niger. *Insects*, *16*(2), 196. tps://doi.org/10.3390/insects16020196
9. Bordolui, S. K. A Multifaceted Approach Combining Identity, Preventive Measures, Sanitation, and Tackling of Storage Insect Pest in the Seed Godown
10. Charoenphun, N., Ban, Z., Liu, L., Paulraj, B., & Venkatachalam, K. (2025). A Review of Post-Harvest Management Practices and Quality Optimization Strategies for Indian Gooseberry (*Phyllanthus emblica L.*). *Trends in Sciences*, *22*(12), 11546-11546.
11. Chigoverah, A. A., & Mvumi, B. M. (2022). Modified atmosphere and hermetic technologies for stored grain protection: An overview of African experiences. *Journal of Stored Products Research*, 95, 102055.
12. Dhakal, S., Bhattarai, B., & Timsina, B. (2022). Effect of temperature and relative humidity on storage stability and quality of legume seeds. Journal of Stored Products Research, 96, 101951.
13. Duranti, M. (2021). Legume proteins and human health. *Foods, 10*(12), 3156.
14. Ekezie, F. G. C., Sun, D. W., & Cheng, J. H. (2021). Emerging nonthermal food processing technologies and their applications in legumes. *Food Engineering Reviews*, 13(1), 45–66.
15. FAO & EU-Knowledge4Policy. (2023). *Evidence on crop postharvest loss reduction interventions in Sub-Saharan Africa and South Asia*. Food and Agriculture Organization.
16. FAO/IAEA. (2023). *Guidelines on the use of irradiation for the control of stored product pests in grains and legumes*. International Atomic Energy Agency.
17. Folle, S. A., Alabi, T., & Baoua, I. (2022). Essential oils as biofumigants for sustainable storage of pulses in West Africa. *Crop Protection, 158*, 106025.
18. Fornaciari, F., Benelli, G., & Canale, A. (2023). Carbon dioxide-based modified atmosphere treatments for stored product pest management: Current advances and future directions. *Insects, 14*(3), 295.
19. Getahun, E., Mamo, T., & Abebe, G. (2023). Evaluation of solar drying technologies for post-harvest loss reduction of pulses in Ethiopia. *Heliyon, 9*(2), e13345.
20. Hassan, M. M., Ghosh, S., & Islam, M. T. (2023). Application of phase-change materials for cold storage of agricultural products: A sustainable approach. *Renewable Energy, 210*, 1025–1038.
21. Jaiswal, S. K., & Dakora, F. D. (2025). Maximizing Photosynthesis and Plant Growth in African Legumes Through Rhizobial Partnerships: The Road Behind and Ahead. *Microorganisms*, *13*(3), 581.
22. Jayanta, P., Poonia, S., & Sharma, A. (2023). Impact of carbon dioxide and oxygen-modified atmospheres on storage stability of chickpea and lentil seeds. *Postharvest Biology and Technology, 201*, 112297.
23. Kifle, T., Alemu, D., & Mekonnen, A. (2021). Fungal infestation dynamics in legume grains under variable storage humidity. *Mycotoxin Research, 37*(4), 289–301.
24. Kilonzo, M. J., Mugo, S., & Ochieng, P. (2022). Evaluation of plant-derived essential oils for control of storage pests in pulses. *Pesticide Biochemistry and Physiology, 184*, 105115.
25. Kokkini, M., Gazoulis, I., Danaskos, M., Kontogeorgou, V., Kanatas, P., & Travlos, I. (2025). Enhancing ecosystem services in agriculture: the special role of legume intercropping. *Frontiers in Sustainable Food Systems*, *9*, 1547879.
26. Kumar, D., & Sharma, R. (2024). IoT-based grain storage monitoring systems: Current trends and future directions. *Computers and Electronics in Agriculture, 218*, 108512.
27. Kumar, P., Raghavan, V., & Mandal, S. (2022). Nanotechnology-based smart packaging systems for improved grain and pulse preservation. *Trends in Food Science & Technology, 125*, 260–274.
28. Kumari, P., Mandal, S., & Raghavan, V. (2023). Advances in solar-powered cold storage technologies for agricultural products: A review. *Renewable and Sustainable Energy Reviews, 180*, 113272.
29. Li, H., Zhang, Y., & Zhao, X. (2024). Effects of temperature and relative humidity on the physicochemical and sensory properties of stored faba and adzuki beans. *Journal of Food Engineering, 354*, 111679.
30. Mehta, A., Sharma, V., & Chauhan, D. (2021). Integration of cold storage and modified atmosphere systems for grain preservation. *Food Control, 125*, 107951.

31. Melese, M., Getachew, B., Woldemeskel, E., & Gunnabo, A. H. (2025). Legume integration in smallholder farming systems for food security and resilience to climate change. *PloS one*, *20*(8), e0327727.
32. Momanyi, M. R., et al. (2022). Effect of hermetic Purdue Improved Crop Storage (PICS) bag on chemical and anti-nutritional properties of common bean (*Phaseolus vulgaris L.*) varieties during storage. *PubMed*.
33. Moses, D. A., Opoku, A., & Adomako, D. (2022). Performance evaluation of hybrid solar-biomass dryer for grain drying in Sub-Saharan Africa. *Renewable Energy, 189*, 1328–1337.
34. Mrázková, M., Sumczynski, D., Šenkárová, L., & Salek, R. N. (2025). Dietary Intakes and Exposures to Minerals and Trace Elements from Cereal-Based Mixtures: Potential Health Benefits and Risks for Adults. *Nutrients*, *17*(17), 2848.
35. Murdock, L. L., Baoua, I. B., & Amadou, L. (2022). Hermetic storage as an alternative to chemical protection of grain legumes. *Frontiers in Sustainable Food Systems, 6*, 867124.
36. Mushtaq, A., Yousouf, M., Malik, M. A., Mukhtar, T., Amin, T., Showkat, S., & Rafiq, A. (2025). Post-harvest quality management of sweet corn: Disorders, losses and preservation strategies. *Food Nutrition*, *1*(1), 100007.
37. Nakimbugwe, D., Nankya, J., & Kyomugisha, R. (2023). Postharvest management and quality of dry beans in smallholder systems of Uganda. *Agriculture & Food Security, 12*(1), 34.
38. Navarro, S., Donahaye, E., & Jayas, D. S. (2021). Advances in modified atmosphere and hermetic storage for grain protection. *Frontiers in Sustainable Food Systems, 5*, 648563.
39. Njoroge, A. W., Kimenju, S. C., & Mutungi, C. M. (2023). Integrated postharvest management of pulses and grains: Synergistic technologies for sustainable storage. *Food Control, 150*, 109753.
40. Ochieng, J., Gwaka, J. E., Radegunda, K., Rubyogo, J. C., Maganga, R., Cheyo, E., & Mwakatwila, A. (2025). Smallholder mechanization: Motivation for and barriers to women and youth in Tanzania.
41. Odjo, S., Regalado, J. G., Tejeda, A. S., Guera, M., & Verhulst, N. (2025). Hermetic bags remain effective in minimizing storage loss after four successive cycles of reuse in Mexican highlands. *Journal of Stored Products Research*, *110*, 102480.
42. Okeke, C. O., Uzochukwu, S. V., & Onuorah, C. (2021). Antifungal potential of *Bacillus* and *Lactobacillus* species against storage fungi in cowpea. *African Journal of Microbiology Research, 15*(4), 189–198.
43. Oliveira, M. M., Alves, E., & Silva, F. (2021). Gamma irradiation for insect disinfestation and preservation of stored pulses. *Radiation Physics and Chemistry, 184*, 109468.
44. Ouili, A. S., Nikiema, M., Compaoré, C. O. T., Dube, Z. P., Kinore, M., Maiga, Y., & Ouattara, A. S. (2025). Postharvest practices and aflatoxin content of cowpea (Vigna unguiculata L. Walp.) grain in Burkina Faso. *Journal of Stored Products Research*, *111*, 102528.
45. Raju, R. N., Heyes, J. A., Archer, R. H., & Chen, Q. (2025). Predicting the dried moisture content in Fijian Theobroma cacao beans using a mechanistic model. *New Zealand Journal of Crop and Horticultural Science*, *53*(2), 232-251.
46. Rana, S., Gupta, R., & Kumar, A. (2022). Plasma-based technologies for post-harvest treatment of pulses: A sustainable approach. *Innovative Food Science & Emerging Technologies, 79*, 103056.
47. Samanta, I., Tarafdar, S., Sahoo, S. S., Saha, S., Mohanty, S., & Chowdhary, G. (2025). Vigna radiata: a Minor Legume with Major Potential. In *Recent Trends and Applications of Leguminous Microgreens as Functional Foods* (pp. 141-178). Cham: Springer Nature Switzerland.
48. Sarkar, S., Das, A., & Ghosh, S. (2021). Solar drying systems for legumes: Design and performance evaluation. *Renewable Energy, 170*, 580–590.
49. Scialabba, N. E., Kumar, A., & Hassan, R. (2021). Controlled atmosphere storage as a sustainable postharvest management option for pulses and oilseeds. *Food Control, 126*, 108069.
50. Singh, P., Rathore, S., & Sharma, V. (2024). Impact of storage on nutritional quality of pulses. *Food Reviews International, 40*(3), 1058–1074.
51. Stagnari, F., Pisante, M., & Diacono, M. (2022). Legume-based systems and their contribution to sustainable agriculture. *Agronomy for Sustainable Development, 42*(6), 85.
52. Suherman, S., Anggoro, D. D., Sugiharto, S., & Asy-Syaqiq, M. A. (2025). Investigation of a mixed-mode solar dryer assisted with an air recycling system and phase change material unit for coffee beans drying: An experimental study. *Renewable Energy*, 123762.
53. Thirumdas, R., Kothakota, A., & Annapure, U. S. (2020). Cold plasma: A novel technique for the preservation of grains and pulses. *Journal of Food Science and Technology, 57*(10), 3561–3571.
54. Wang, Z., Li, Q., & Zhao, Y. (2023). Ozone-based postharvest technologies for microbial and pest control in stored agricultural products. *Food Control, 150*, 109756.
55. Zaman, W., Amin, A., Khalil, A. A. K., Akhtar, M. S., & Ali, S. (2025). Plant–Microbe Interactions for Improving Postharvest Shelf Life and Quality of Fresh Produce through Protective Mechanisms. *Horticulturae*, *11*(7), 732.
56. Zhang, X., Zhu, C., Geng, D., Cheng, Y., & Tang, N. (2025). Characterization of dynamic of the structural changes of legume starches during gelatinization. *International Journal of Biological Macromolecules*, *296*, 139673.
57. Zhang, Y., Li, J., & Hu, W. (2023). Temperature–humidity interactions on protein solubility and texture in stored legumes. *Food Chemistry, 406*, 135063.
58. Zhou, X., Lin, H., & Liu, C. (2022). Development of multifunctional nanocomposite films for legume preservation and quality enhancement. *Food Packaging and Shelf Life, 34*, 100980.