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REVIEW ARTICLE

Enhancing seed shelf life through modified atmospheric packaging: Mechanisms, benefits and future prospects

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Abstract

Efficient seed storage is crucial for maintaining seed quality, viability and germination potential, which directly impact agricultural productivity and food security. However, prolonged storage leads to seed deterioration due to both biotic and abiotic factors, resulting in significant post-harvest losses. Modified atmospheric packaging (MAP) is a sustainable non-chemical technology that enhances seed storability by altering the gaseous environment around seeds. MAP operates through active packaging, which injects desired gases and passive packaging, where the product's respiration modifies the atmosphere. By reducing oxygen (O_2) levels, minimizing moisture absorption and inhibiting microbial and insect activity, MAP extends seed shelf life. Typically, O_2 is replaced with nitrogen (N_2) or carbon dioxide (CO_2), limiting oxidative reactions and metabolic activity. MAP benefits multiple seed types, including cereals, legumes, oilseeds and horticultural crops. Physically, it reduces seed moisture, delaying deterioration and preserving seed coat color. Physiologically, it prolongs seed longevity by reducing the accumulation of reactive oxygen species (ROS) and conserving seed reserves. Biochemically, it minimizes lipid peroxidation, maintains enzyme activities like alpha-amylase and catalase and reduces electrolyte leakage. Additionally, MAP controls storage pests and pathogens; elevated CO_2 inhibits insect proliferation and fungal contamination, mitigating mycotoxin risks. This review examines the strategic role of MAP in seed conservation for sustainable agriculture by comparing MAP with traditional storage methods and assessing its impact on seed viability and longevity.

Keywords: modified atmospheric packaging; packaging technology; seed storage; seed quality; shelf life

Introduction

A seed is a ripened ovule consisting of an embryo and a protective seed coat. Seeds contain reserve materials such as starch, oils and proteins, which are utilized during germination and are typically found in the endosperm or cotyledons (1). They represent the fruits of plant breeding and differ from grains, which are meant for food or raw materials. After harvesting, the seeds are dried to optimum moisture content (depending upon crops) and stored to maintain the initial seed quality until they are needed for planting. Proper storage conditions can preserve seed vigour and germination, which directly impact crop yield (2). Seed storage methods have evolved from ancient to modern times, with traditional practices like bamboo bins and earthen pots (3) and modern practices like ultra-cold storage and cryopreservation (4). Seed storage serves as a buffer between demand and production, maintains genetic resources and preserves seed viability (5).

However, during the extended storage period, the seed undergoes deterioration, which is an undesirable and detrimental attribute of agriculture. Oxidative damage caused by reactive oxygen species (ROS) is a primary factor in seed aging, leading to protein oxidation, chromosomal abnormalities and DNA damage (6). Three-phase of hypothesis for seed deterioration was reported (7). This process is a separate event from seed development and germination (8). Several biotic (insect Infestation and pathogen infection) and abiotic (temperature, relative humidity, oxygen and moisture content) factors contribute to seed deterioration, making it very difficult to maintain viability during storage. Seed quality depends upon initial seed quality, temperature, moisture content and mycoflora (9). It is estimated that 25-33 percent of the world grain crop, including seeds, is lost each year during storage (FAO). These losses reduce the efforts taken to increase agricultural production and the availability of quality seeds. Proper seed management practices during the storage period can minimize these losses (10), which can be implemented through modified atmospheric packaging (MAP). It has emerged as a promising approach to extending seed storability and maintain seed quality by reducing moisture content and oxygen levels and preventing insect infestation and pathogen infection (11).

MAP is defined as introducing carbon dioxide (CO_2) or nitrogen (N_2) into a storage container and restricting the concentration of oxygen (O_2) (12). It is the practice of packaging a perishable product that is kept in an atmosphere that has been modified. Hence the composition altered from the original atmosphere (13). MAP in seed storage is the best alternative to the use of chemicals and insecticides, which leave carcinogenic residues in the treated products (14). MAP differs from other non-chemical preservation methods, such as vacuum packaging and controlled atmosphere storage (CAS). While vacuum packaging eliminates oxygen, it lacks flexibility in gas exchange, which can be crucial for seeds requiring some metabolic activity (15). CAS, on the other hand, maintains a continuously monitored balance of gases but is more resource-intensive and costly (16). MAP provides gas modifications without the need for continuous monitoring, making it both adaptable and cost-effective.

MAP is preferred over conventional seed storage techniques due to its ability to create gaseous environments that optimize seed viability and longevity (17). It offers a sustainable chemical-free alternative that reduces oxidative stress and microbial contamination (18). This technology is particularly relevant in addressing climate-related storage challenges, such as fluctuating temperatures and increased humidity, which accelerate seed deterioration (19). By mitigating these environmental stresses, MAP enhances food security and supports resilient agricultural practices in the face of climate change. MAP's ability to maintain the catalase, peroxidase and alpha-amylase activity when the onion seeds are stored under CO_2 storage conditions (20). Similarly, the impact of MAP on groundnut kernel storage and found that N_2 storage significantly extended the shelf life while maintaining a higher germination rate (21). These studies reinforce the potential of MAP as a viable alternative to conventional storage.

Methodology

This review utilized Scopus, Web of Science and Google Scholar to ensure a comprehensive selection of studies. Inclusion criteria focused on peer-reviewed articles published since 2010 that examined the role of MAP in seed storage and conservation. Studies without empirical data or those centered solely on food packaging were excluded. Keyword searches included terms such as “MAP in seed storage,” “seed viability under MAP,” and “enzyme activity under MAP.”

Packaging techniques for modified atmospheric

The packaging of modified atmospheric (MA) condition can be established with two approaches, such as

Active packaging

Active packaging involves creating a modified atmosphere inside a container by first applying a vacuum and then replacing the air with a specific gas mixture. This method can incorporate ethylene scavengers or emitters, which work together to establish the desired MA within the sealed package rapidly. Compared to the passive technique, the active packaging process is more efficient and less time-consuming (22). It is commonly used for preserving vegetable seeds, fresh-cut fruits and nuts (23).

Passive packaging

Passive packaging, also known as commodity-generated MAP, forms naturally within a sealed container due to the respiration process of the product, where O_2 is consumed and CO_2 is released. In this method, the packaging material allows oxygen to permeate into the container while excess CO_2 escapes. When the respiration rate of the product aligns with the gas permeability properties of the packaging film, a beneficial MA is created inside the container (24). This type of packaging is particularly suitable for storing potato tubers (25).

Applications of modified atmospheric packaging

MAP is a widely used technology for extending the shelf life and maintaining the quality of various perishable products, including fruits (26), vegetables (27), marine foods (28) and preserving food quality (29). It is highly beneficial for increasing the shelf life of processed foods. It reduces the availability of O_2 to microbes, retard their growth and allowing food to be preserved for an extended period. It also reduces all metabolic activity and respiration rates within the packing. It preserves the food item's original form and makes it appealing to the consumer. It also reduces the loss of moisture from the packaged food product. In agriculture, MAP helps in preserving seed quality during storage. It slowed the deterioration process and maintained higher physiological quality (30). During storage, there was less reduction in enzyme activity, protein content and seed leachate (31). Gases used in modified atmospheric packaging

Oxygen

It promotes the growth of aerobic bacteria while inhibiting the growth of anaerobic bacteria. In modified atmosphere packaging (MAP), oxygen plays a key role in maintaining myoglobin in its oxygenated form, oxymyoglobin. Usually, seed deteriorates quicker at higher storage temperatures, seed moisture content, or in the presence of high O_2 levels (32). A high O_2 level at storage reduces seed longevity (33).

Nitrogen

It is an inert, tasteless gas with minimal antibacterial properties. Because of its limited solubility in water, the addition of N_2 in MAP food helps avoid pack collapse caused by high CO_2 concentrations. Furthermore, by replacing O_2 in the pack, N_2 can slow oxidative rancidity while also inhibiting the growth of aerobic microbes (18).

Carbon dioxide

It is soluble in both water and lipids and it is primarily responsible for the bacteriostatic effect observed on microbes cultured in MA conditions. The antimicrobial effects of CO_2 were first noted in 1877 by Pasteur and Joubert, who found it could kill *Bacillus anthracis* (34). The CO_2 prolongs the microbial lag phase and slows growth during the logarithmic phase of development. For practical purposes, in most diets, gaseous CO applied to a living tissue would exist predominantly as soluble CO_2 gas and carbonic acid (35).

Gas composition and film permeability

The composition of gases in MAP plays a critical role in seed preservation. High CO_2 levels suppress microbial growth and insect activity, while reduced O_2 levels limit oxidative stress and metabolic degradation (36). N_2, being an inert gas, helps maintain a stable atmosphere by displacing O_2, reducing lipid peroxidation and enzymatic degradation (37). MAP effectiveness is significantly influenced by film permeability. It determines how gases like O_2 and CO_2 can pass through the film, which in turn affects the respiration rates of the produce and the overall atmosphere inside the package. Different types of polymeric films, such as polyvinyl chloride (PVC) and polyvinylidene chloride (PVDC), are utilized in Modified Atmosphere Packaging (MAP). These films have varying gas transmission rates (GTR) and water vapor transmission rates (38). The GTR of a film increases with the storage temperature and the magnitude of this increase varies with the film type and thickness. This helps in maintaining the quality of the produce for a longer period by reducing respiration rates, ethylene sensitivity, decay and physiological changes (39).

Nanomaterials can significantly enhance the barrier properties of packaging films, thereby reducing permeability to gases such as O_2 and CO_2. This helps in maintaining the desired atmosphere inside the package, which is crucial for preserving seed viability. Nanomaterials, such as silver nanoparticles, have antimicrobial properties. Incorporating these into packaging films can help protect seeds from microbial contamination, reducing the risk of seed-borne diseases. Nanomaterials can improve the mechanical strength of packaging films, making them more resistant to physical damage. This is particularly important for protecting seeds during transportation and storage (40).

Modified atmospheric packaging on seed quality during storage

Physical seed quality attributes

Moisture content: The primary factor contributing to seed deterioration during storage is high moisture content, which leads to reduced germination capacity (41). Seeds are inherently hygroscopic, meaning their moisture content fluctuates in response to changes in atmospheric humidity and temperature. When seeds are stored in gunny or cloth bags, they readily reach a state of moisture equilibrium with the surrounding environment. However, MAP conditions help to prevent moisture absorption from the external environment, thereby extending seed viability.

Research has demonstrated the effectiveness of MAP in reducing moisture content and preserving seed quality over time. In groundnut, the kernels stored under N_2 recorded low moisture content (7.0%) compared to other storage conditions at the end of 6 months of storage period (21). For instance, kabuli chickpea seeds stored in the MAP with a combination of 80% CO_2, 20% N_2 and 0% O_2 showed a low moisture content of 8.03% at the end of 14-month storage period, compared to the control (8.42%) and the germination percentage was recorded at a maximum of 92.38% due to low moisture content (42). Similarly, green gram seeds stored in an environment with 40% CO_2 maintained a low moisture content of 8.42% at the end of 6-month storage period (43). In another study, the onion seeds exposed to MAP for 12 months, with an initial moisture content of 6.10%, were subjected to 15 treatment combinations. Among these, the combination of 80% CO_2, 5 % O_2 and 15 % N_2 showed a minimal increase in moisture content, reaching only 6.17% at the end of the storage period. In contrast, seeds stored in cloth bags recorded the highest moisture content of 8.17% (44) (Table 1). Through MAP, the moisture content can be maintained within the permissible limit during storage, thereby preventing deterioration and extending seed viability (11, 45).

Seed coat color: The MAP techniques have demonstrated significant effects on preserving seed coat color by reducing O_2 levels, which slows the rate of oxidative reactions. The oxidative reactions are a primary cause of color deterioration as they affect anthocyanin pigment, which is responsible for seed coat color (46). The low-O_2 environments enhance pigment stability, thereby preventing browning or darkening of the seed coat (47, 48).

Research in various legumes and fruits illustrates the benefits of MAP in preserving seed quality. For instance, lentil seeds are stored in aluminum-laminated bags with N_2, CO_2 and air at temperatures of 15°C and 35°C. The N_2 and CO_2 present in atmosphere maintained seed coat color, germination percentage and hydration capacities over extended storage periods across temperature variations (49). Similarly, faba bean seeds are stored under CO_2, N_2, O_2 and vacuum conditions at 30°C in darkness for a year. The N_2 storage exhibited reduced color darkening and minimized tannin losses, maintaining the quality of seeds during long-term storage (50) (Table 1). Furthermore, pomegranate seeds stored in MAP at 1°C effectively retained anthocyanin levels (47). These findings underscore the importance of low-O_2 environments for pigment preservation and MAP conditions, significantly slowing down the anthocyanin degradation and helping to retain color and quality attributes in seeds and fruits during storage.

Physiological seed quality attributes

Seed longevity is intricately linked to various physiological traits such as germination percentage, root and shoot length, dry matter production, vigour index and speed of germination (45). A significant factor affecting seed longevity is reactive oxygen species (ROS). They act as a dual role in seed physiology, serving as signaling molecules at controlled levels to support germination but causing oxidative damage and cellular degradation when they

Table 1. Effect of Modified Atmospheric Packagingon the physical and physiological quality of seeds

	Sl. No.	Seeds and their storage duration	Impact of Modified Atmospheric Packaging	Reference
Physical seed quality	1.	Groundnut (6 months)	At the end of 6 months of storage, kernels stored in N_2 recorded low moisture content (7.0%) compared to other storage conditions	(21)
	2.	Chickpea (14 months)	Low moisture content (8.03%) recorded at the end of 14 months of storage period compared to control (8.42%) under 80% CO_2 + 20% N_2 + 0% O_2 gas combination	(42)
	3.	Green gram (6 months)	Storing seeds under 40% CO_2 gas, moisture content (8.42%) is maintained at the end of the storage period compared to control	(43)
	4.	Onion (12 months)	In the 80% CO_2 + 5 % O_2 + 15 % N_2 gas combination, there was the minimum increase in moisture content (6.17%) at the end of the storage period compared to the control (8.17%)	(44)
	5.	Lentil (12 months)	The N_2 and CO_2 atmospheres maintained the seed coat colour, germination percentage and hydration capacities throughout the storage period	(49)
	6.	Faba bean (12 months)	Storing seeds under N_2, reduces colour darkening and tannin losses, which would be useful in maintaining the quality of seeds during long-term storage.	(50)
Physiological seed quality	7.	Groundnut (8 months)	Stored under N_2 at -5°C condition, maintained germination above 70% even after 8 months of storage period	(54)
	8.	Groundnut (12 months)	40 percent CO_2 atmosphere storage maintains the vigour and viability up to 12 months of storage	(53)
	9.	Amaranth (7 years)	Under the N_2 condition, the viability and vigour are maintained for 7 years under the ambient storage condition	(55)
	10.	Horse gram (6 months)	Maximum germination (89%) is observed at the end of storage period by storing under 50% CO_2 atmosphere	(56)

accumulate excessively (51). MAP plays a crucial role in mitigating these effects by reducing O_2 levels and enhancing CO_2 and N_2 concentrations, which in turn slows down seed respiration rates and limits ROS production, thus preserving the seed's food reserves available to the seeds (52).

Research highlights the effectiveness of MAP in extending seed viability across various species. Groundnut pods or kernels with 8% moisture content stored either in the storage environment of 10°C with 40% RH or 40% CO_2 concentration can maintain vigour and viability for up to 12 months (53). Another study on groundnut stored with a 100% N_2 gas at -5 °C condition maintained germination above 70% even after 8 months of storage period (54). When the amaranth seed stored with N_2 gas in laminated aluminium foil pouches maintained viability and vigour for nearly 7 years under the ambient storage condition (55). Similarly, horse gram seeds are stored in 50% of CO_2 and recorded maximum germination of 89% at the end of the six -month storage period (56) (Table 1). Overall MAP, especially under conditions involving N_2, CO_2 and vacuum, effectively preserves the seed vitality.

Biochemical seed quality attributes

Seed storage studies reveal that biochemical changes during deterioration significantly impact seed quality and viability. During aging, enzymes *viz.*, alpha-amylase, peroxidase, catalase, dehydrogenase and superoxide dismutase are positively correlated with seed quality (45) and decrease in various crops like wheat (57), soybean (58), onion (59) and groundnut (60). These enzymes play a crucial role in maintaining seed viability by scavenging free radicals produced during deterioration. Conversely, lipase activity increases with storage time and is negatively correlated with seed quality (60). Additionally, seed deterioration is associated with increased lipid peroxidation and higher electrical conductivity (EC) of seed leachates (59). Understanding these enzymatic and biochemical changes can help to predict seed storage life and develop strategies to maintain seed quality during storage.

Alpha-amylase breaks down starch into simpler sugars, providing energy for seed germination (61). Reduced O_2 levels in MAP can slow down the activity of alpha-amylase, thereby reducing the rate of starch breakdown. This helps in conserving energy reserves and prolonging seed viability. The activity of peroxidase and catalase enzymes in seeds decreases during storage and leading to a decline the seed viability (60). This decline is associated with an increased accumulation of hydrogen peroxide (H_2O_2) and malondialdehyde content, as well as decreased germination and membrane deterioration (62). The reduced O_2 leads to lower ROS production. Peroxidase activity helps maintain cellular homeostasis by breaking down any formed ROS, thus protecting the seeds from oxidative damage. Similar to peroxidase, catalase activity is crucial in MAP for mitigating oxidative stress. The enzyme's activity ensures that any H_2O_2 produced during metabolic processes is efficiently broken down, preventing cellular damage (63). During stressful conditions; superoxide dismutases are produced and act as a defense mechanism against oxidative stress in plants and seeds. Additionally, these superoxide dismutases possess free radical scavenging properties by stabilizing the carbon bonds in free radicals (64). When the onion seeds were stored under CO_2 storage conditions with seed coating, they maintained storage potential by recording higher catalase, peroxidase and alpha-amylase activity (20). The dehydrogenase enzyme activity is a stable marker to estimate the degree of viability in seeds during storage. During storage, the enzyme activity is reduced and it is maintained under MAP conditions. The groundnut seeds exposed to the gas combination of 60% N_2+ 0% O_2+ 40% CO_2 showed higher dehydrogenase activity (0.133 OD value) compared to the control (0.068 OD value) at the end of ten month storage period (11) (Table 2).

Table 2. Effect of Modified Atmospheric packaging on Biochemical quality and seed Health Activity of seeds

	Sl. No.	Seeds and their storage duration	Impact of Modified Atmospheric Packaging	Reference
Biochemical seed quality	1.	Pigeon pea (10 months)	Under 40% N_2 + 60% CO_2 gas combination, less seed leachate (2.029 dSm^{-1}) recorded when compared to control (2.207 dSm^{-1}) at the end of storage period	(31)
	2.	Sorghum (10 months)	Less seed leachate (1.001 dSm^{-1}) compared to control (1.265 dSm^{-1}) when seeds stored under 40% N_2 + 60% CO_2 gas combination	(67)
	3.	Groundnut (10 months)	60% N_2 +40% CO_2 combination showed higher dehydrogenase activity (0.133 OD value) compared to the control (0.068 OD value) at the end of ten months storage period	(11)
	4.	Onion (6 months)	Storing seeds under CO_2 conditions recorded higher catalase, peroxidase, alpha amylase activity	(20)
Seed Health activity	5.	Green gram (6 months)	45% CO_2 was effective in reducing bruchid infestation and subsequent progeny production for up to 2 months after storage	(71)
	6.	Horse gram (6 months)	Seeds remained free from insect damage for up to six months under CO_2 (50%)	(56)
	7.	Wheat (6 months)	20 percent of CO_2 was effective in achieving total insect mortality within a two month exposure period	(72)
	8.	Maize (17 weeks)	Formation of mycotoxin is prevented by storing seeds under 90% CO_2 + 5% O_2 + 5% N_2	(76)
	9.	Groundnut (15 weeks)	Suppress the occurrence of mycobiota and preserve the quality of kernels in terms of color and lipid oxidation and reduce aflatoxin B1 contamination under 100% CO_2, 100% N_2 and vacuum packaging	(77)

Lipase is a fascinating catalytic enzyme that facilitates the hydrolysis of ester bonds in triglycerides into free fatty acids and glycerol. It is negatively correlated with the seed quality. The higher accumulation of lipase enzyme was also evidenced by the higher accumulation of free fatty acids in seeds (60). The EC assesses the condition of a seed's cell membranes by measuring conductivity. During storage, the EC of seed leachates increases primarily due to the loss of membrane integrity at the cellular level, resulting in the release of macromolecules and electrolytes from seed cells. This process involves both passive diffusion of low molecular weight solutes and the release of macromolecules from ruptured cells. The leakage of intracellular substances, particularly enzymes and electrolytes, depends on the loss of testa integrity and subsequent cellular membrane damage due to oxidative stress (65). Seeds of inferior quality typically exhibit a weakened membrane structure, leading to the leakage of essential electrolytes like amino acids and inorganic ions (66). These substances are crucial for the rapid development and emergence of seedlings. Storing seeds under MAP conditions with reduced O_2 levels can decrease oxidative stress on seeds, which helps to preserve membrane integrity and retain nutrients, thereby maintaining seed quality and vigor. The investigation on MAP was conducted with pigeon pea seeds stored in a gaseous combination of 40% N_2, 0% O_2 and 60% CO_2. The results showed that the seed leachate was lower (2.029 dSm^{-1}) in the MAP treatment compared to the control, which recorded a leachate value of 2.207 dSm^{-1} at the end of a 10-month storage period (31). Similarly, in a study on sorghum seeds stored under MAP, a reduced seed leachate value of 1.001 dSm^{-1} was recorded in the same gas combination of 40% N_2, 0% O_2 and 60% CO_2, compared to the control, which had a higher leachate value of 1.265 dSm^{-1} (67) (Table 2). These findings indicate that storing seeds under MAP significantly reduces the leakage of electrolytes and macromolecules from the seeds, as evidenced by the lower electrical conductivity (EC) values. This suggests that MAP can help preserve membrane integrity by minimizing oxidative stress and reducing metabolic activity, which in turn leads to slower deterioration and better seed quality over time.

Seed health activity

Storage insects: Pests that infest stored grains can result in significant damage to the seeds. The extent of this damage is influenced by factors such as temperature, humidity and moisture levels during storage. Alterations in atmospheric conditions, such as increased CO_2 levels and decreased O_2 concentrations, can lower the metabolic activity of insects to a point where combined with the buildup of toxic byproducts, it leads to their demise (68). Modified atmosphere techniques, which involve adjusting the composition of gases surrounding the stored seeds, serve to diminish both the respiration rate of seeds and the activity of insects or microorganisms within them (69). In the case of groundnuts (11) and wheat (70) the N_2 or CO_2 gases are lethal to insects. Therefore, methods utilizing MA enriched with either N_2 or CO_2 are employed to manage insect infestations in storage. A study on the impact of various concentrations of CO_2 on seed infestation and population growth in green gram was performed and research indicates that green gram seeds infested with bruchids and subjected to CO_2 concentrations of 45% or higher exhibit significant effectiveness in reducing bruchid infestation and subsequent progeny production for up to 2 months after storage. Moreover, these treatments maintain a high germination percentage and seedling vigor (71). In Horse gram, seeds exposed to 40% and 50% CO_2 remained free from insect damage for up to six months. When the CO_2 was less, such as 30% or untreated, it showed higher levels of seed damage, with 3.23% and 15.33%, respectively. MS with elevated CO_2 concentrations effectively prevented the emergence of adult *Callosobruchus chinensis* insects during the six-month storage period (56). In wheat seeds, storage insects can be controlled by exposure to 20% CO_2, which has proven effective in achieving total insect mortality within a two-month exposure period. If the CO_2 level is low such as 5% and 10%, results in partial reductions in population growth compared to the control. So this study shows the importance of utilizing an optimal CO_2 concentration for efficiently controlling insect populations and reveals the potential of CO_2 as a viable method for pest management (72) (Table 2). MA eradicates insects from stored products without contaminating the atmosphere and is safer than fumigants (73).

Seed pathogens: The moisture content of the seeds influences the biodiversity of fungi contaminating the seeds, which can, in turn affect their storage life and viability (74). The presence of specific mycoflora, such as *Aspergillus terreus*, *A. flavus*, *Penicillium expansum*, *P. frsquentans*, *P. reprens* and *P. patulum*, can lead to degradation of seeds, particularly in the presence of increased relative humidity (75). MAP with elevated levels of CO_2 is effective in reducing infestation and progeny production, as well as maintaining seed quality (56). When the maize seed is exposed to a gas composition of 90% CO_2+ 5% O_2+ 5% N_2 prevents mycotoxin formation. This highlights the potential of MAP, particularly in the context of elevated CO_2 levels, as a strategy to mitigate mycotoxin contamination in stored maize (76). The studies on groundnut suggest that MAP containing 100% CO_2, 100% N_2 and vacuum packaging exhibit the potential to suppress the occurrence of mycobiota and preserve the quality of kernels in terms of color and lipid oxidation and reduce Aflatoxin B1 contamination (77). When radish seed treated with chlorine dioxide and exposed to MA conditions, 5 or 10% O_2 with 10% CO_2 and no *Cronobacter* spp. were detectable on seeds treated with 100 mL/mL aqueous ClO_2. Moreover, 94.3% of the radish seeds germinated successfully after ClO_2 treatment, followed by exposure to MA conditions (78) (Table 2).

Future studies and cost-effective of MAP

Future studies should focus on assessing MAP's effectiveness under varying environmental conditions, including temperature fluctuations, humidity levels and different seed types. Investigating the integration of smart sensors for real-time monitoring of gas compositions and seed viability would further enhance the applicability of MAP. Additionally, research into biodegradable packaging alternatives could improve the sustainability of MAP, making it an even more viable solution for global seed conservation efforts. MAP is a cost-effective solution compared to traditional storage methods, particularly for smallholder farmers. While initial setup costs for MAP packaging may be higher than conventional storage bags, its long-term benefits outweigh the expenses. By reducing post-harvest losses, minimizing dependency on chemical treatments and extending seed viability, MAP offers economic advantages that improve seed accessibility and profitability for farmers operating on limited resources.

Conclusion

Modified atmospheric packaging (MAP) provides a transformative and sustainable solution for addressing the challenges of seed storage and deterioration. Traditional storage methods are limited by their inability to effectively manage factors such as moisture content, O_2 exposure and microbial or pest infestations, which accelerate seed aging and reduce viability. This review has demonstrated that MAP significantly improves seed quality by creating controlled environments with reduced O_2 and elevated N_2 or CO_2 levels. Despite its demonstrated advantages, MAP adoption faces challenges, including optimizing gas mixtures, packaging materials and economic feasibility for different seed varieties. Addressing these limitations through advanced technologies and improved infrastructure will be crucial for broader implementation. Future research should focus on refining MAP techniques, integrating smart sensors and developing cost-effective packaging solutions to maximize its impact. In conclusion, MAP represents a promising advancement in seed storage technology. Its ability to preserve seed quality and extend shelf life aligns with global efforts toward sustainable agricultural practices and food security. Wider application of MAP, supported by continued innovation, will ensure resilient seed systems and enhanced productivity, making it a cornerstone of modern seed management strategies.

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Authors' contributions

PK & KT were involved in the preparation of the article, including data collection, drafting and editing the manuscript. PK & VV originated the idea for the review and developed its structure. BR & KR evaluated the manuscript and provided continuous support in revising and completing it. KS, VV, SPV & HJ contributed by critically reviewing and refining the manuscript.

Compliance with ethical standards

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