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REVIEW

A Review on Seed Storage Technology: Recent Trends and Advances in Sustainable Techniques for Global Food Security

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Abstract
Seed storage innovation assumes an essential part in guaranteeing worldwide food security by safeguarding genetic variety and preserving seed feasibility over time. This review article gives a complete outline of ongoing patterns and advances in supportable seed stockpiling strategies. Starting with an investigation of the significance of seed storage about food security challenges, the audit digs into conventional seed storing strategies and their obstacles. Additionally review also provides a comprehensive analysis of maintainable methodologies like controlled air capacity, cryopreservation, and seed preparing, featuring their adequacy in dragging out seed suitability while diminishing energy utilization and natural effect. Moreover, the review discusses the incorporation of digital technologies, for example, artificial intelligence and blockchain, in seed storage management to enhance the traceability and convenience of seed collections. Additionally, the role of community-based seed banks and participatory plant breeding in promoting seed resilience against climate change is explored. By discussing current research findings and practical applications, this review aims to inform policymakers, researchers, and practitioners about the diverse range of sustainable seed storage solutions available to safeguard global agricultural biodiversity and ensure food security in the face of evolving ecological challenges.

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Statement of Sustainability: This review focused on enhancing global food security by exploring recent advancements in sustainable seed storage technology. By reviewing emerging trends, this paper aims to highlight innovative techniques that minimize environmental impact while ensuring long-term seed viability. These techniques address the urgent need to conserve genetic diversity and safeguard future crop yields. For sustainable development goals (SDGs), this review contributes to a more resilient and sustainable agricultural system, fostering a harmonious balance between human needs and ecological preservation for generations to come.

1. Introduction

A major problem of the twenty-first century is to provide food security in the face of an expanding worldwide population. A key component of this difficulty is the ability to produce and store seeds sustainably, as seeds are the basis of agricultural output (Garcia-Mier et al., 2014). In order to maintain plant species' genetic variety and guarantee a steady supply of superior seeds for upcoming farming projects, seed storage technology is essential (Pathirana and Carimi, 2022). The current developments and trends in seed storage technology, with an emphasis on environmentally friendly methods, might improve food security worldwide (Ronald, 2011). The resilience of food systems is largely dependent on agricultural biodiversity, which provides the genetic resources needed for crops to adjust to shifting environmental circumstances as well as shifting pest and disease challenges (Altieri et al., 2015). Since seeds are the genetic diversity's bearers, storing them properly is essential to maintaining the base of our food supply. However, problems with pests, illnesses, and environmental changes have plagued conventional seed storage techniques (Fowler and Mooney, 1990). To overcome these obstacles and preserve our agricultural legacy, we investigate and apply cutting-edge, sustainable seed storage technology (Balyan et al., 2024). Farmers have always depended on conventional seed storage techniques including open-field drying and container storage (Sudhakar et al., 2020). Although these techniques have had some success, there are several hazards associated with them, such as moisture-induced seed degradation, temperature swings, and insect and disease infestations. Additionally, traditional seed storage methods are not scalable enough to satisfy the needs of contemporary agriculture. The weaknesses of these conventional approaches become increasingly obvious as global climate patterns continue to change and extreme weather events occur more frequently and intensely (Altieri and Koohafkan, 2008). This emphasizes how important it is to use cutting-edge, durable, and sustainable seed storage systems. More advanced and effective techniques have become the norm in seed storage technologies in recent years (Balyan et al., 2024). Seed vaults and gene banks are examples of controlled-environment seed storage facilities that have gained popularity because they may offer the best conditions for preserving seeds (Joshi, 2021). The development of technology such as cryopreservation has made it possible to store seeds for lengthy periods at extremely low temperatures, maintaining their genetic integrity and viability (Kaviani, 2011). Furthermore, the incorporation of digital technology, such as artificial intelligence and sensor networks, has made it possible to monitor seed storage conditions in real-time and take proactive measures to stop degradation (Ataei et al., 2023). In contemporary agriculture, sustainability has emerged as a guiding concept, and seed storage is no different. Long-term resilience, resource efficiency, and environmental impact reduction are given top priority in sustainable seed storage methods (De Boef, et al., 2010). This entails creating environmentally friendly seed packing materials, building energy-efficient storage facilities, and building the infrastructure for seed storage using renewable energy sources (Cheng et al., 2014). In addition, the use of naturally occurring substances possessing antimicrobial qualities as seed treatments promotes insect resistance without depending on artificial pesticides (Bonome et al., 2020). International cooperation in seed banking has become essential for improving food security in a time of linked economies and common environmental issues (Grote, 2014). International seed banks, like the Svalbard Global Seed Vault, are prime examples of how countries work together to build safe seed vaults that guarantee the supply of vital crops throughout the world during emergencies (Rimmer, 2012). International germplasm exchange encourages crop variety and aids in agriculture's adaptation to changing environmental circumstances (Smith et al., 2021). Even while seed storage technology has advanced significantly, problems still exist. Complex challenges that require careful thought are raised by issues including the fair allocation of seed banking resources, the possibility of gene piracy, and the ethical implications surrounding genetic manipulation in seed storage. Looking ahead, these obstacles must be overcome by further research and innovation in seed storage technology to guarantee that developments improve global food security while upholding moral and environmental standards (Tansey and Rajotte, 2008).

Therefore, this review article focuses on exploring the recent trends for enhancing global food security through recent advancements in sustainable seed storage technology and how it can contribute to achieving sustainability in the agri-food chain.

2. Importance of Seed Storage in Agriculture

Seed banks are essential for the conservation of a wide range of plant genetic material, which is crucial for the maintenance of genetic diversity. This diversity is vital for breeding programs as it enables plants to adapt to changing environmental conditions and resist pests and diseases (Salgotra et al., 2023). Seed storage methods also contribute to preserving biodiversity by safeguarding seeds from various plant species. Biodiversity plays a crucial role in maintaining the overall health and resilience of ecosystems (Walters and Pence, 2021). Gene banks store seeds that serve as a valuable resource for researchers and plant breeders. These seeds can be used for the development of new crop varieties with improved traits, such as higher yields, resistance to disease, and tolerance to environmental stresses (Wimalasekera, 2015). Seed banks offer a form of insurance against natural disasters, climate change, or other catastrophic events that can lead to crop loss. They allow for the recovery and re-establishment of crops after such incidents (Singh et al., 2013). In addition to crops, seed banks often store seeds from endangered plant species. This helps prevent the extinction of these species and can be a crucial component of conservation efforts. Preserving a diverse range of seeds is crucial to ensuring global food security, as it provides the raw material for developing crops that are resilient and adaptable to changing environmental conditions, which is particularly important in the face of challenges such as climate change and population growth (McGuire and Sperling, 2013). This is because it provides the raw material for developing crops that are resilient and adaptable to changing environmental conditions, which is particularly important in the face of challenges such as climate change and population growth (McGuire and Sperling, 2013). This is because it provides the raw material for developing crops that are resilient and adaptable to changing environmental conditions, which is especially important in light of challenges such as climate change and population growth (McGuire and Sperling, 2013). Seed banks also play a vital role in scientific research and education by providing a repository of genetic material for study (Salgotra et al., 2019). This allows researchers to study the genetic basis of traits, investigate how plants have evolved, and explore how different species relate to one another (Figure 1).

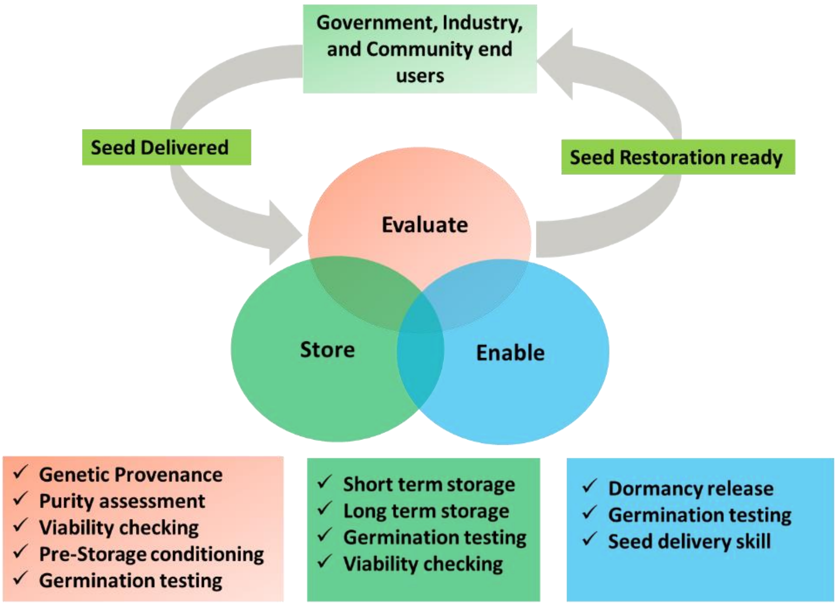

Figure 1. Various components and supply chain of seed storage technologies.

3. Historical Challenges in Conventional Seed Storage Methods

Throughout history, conventional seed storage procedures have faced numerous challenges. These challenges have led to issues such as reduced seed viability, genetic degradation, and susceptibility to pests and diseases (Kameswara et al., 2017). Traditional methods of storing seed were often vulnerable to fluctuating temperatures and humidity, which could adversely affect seed quality. High temperatures and humidity may lead to seed germination or encourage the growth of fungi and bacteria. Stored seeds are at significant risk of damage from insects, rodents, and other pests (Kameswara et al., 2017). Conventional storage facilities are often insufficiently sealed, allowing pests to access and damage the seeds, resulting in losses in both quantity and quality. Traditional storage containers are frequently not airtight, making seeds vulnerable to exposure to air and moisture. Seed deterioration and loss of germination potential can result from exposure, as noted by Bishaw et al. (2007). Conventional storage approaches have lacked sophisticated monitoring and control mechanisms, making it challenging to track and manage environmental conditions within storage facilities. Tracking and managing environmental conditions within storage facilities was challenging, which led to suboptimal storage conditions and increased risk of seed deterioration (Chhabra and Singh, 2019). Continuous planting of seeds from the same source without proper storage and preservation measures can lead to genetic erosion (Peres, 2016). This loss of genetic diversity can make crops more vulnerable to pests, diseases, and environmental stresses (Jump et al., 2009). Diverse seed storage practices were employed by different regions and communities, resulting in inconsistencies in quality and viability. Standardization and widespread adoption of these methods were also lacking (Zinnen et al., 2021). Effective storage methods were historically hindered by limitations in scientific knowledge and technological advancements. The lack of understanding of the physiological processes involved in the degradation of seeds made it difficult to formulate effective strategies for their preservation (Copeland and McDonald, 2012). Traditional methods have faced difficulties in ensuring the long-term viability of seeds. Certain plant species have inherently difficult-to-store seeds that can lose viability over time (Kameswara et al., 2017). To address these challenges, improved seed storage techniques have been developed, including controlled atmosphere storage, refrigeration, and the use of hermetic storage containers (Afzal et al., 2019). These modern techniques aim to better manage environmental conditions, reduce pest infestation, and increase stored seed longevity.

2.1. Environmental Impact of Traditional Seed Storage

Traditional seed storage procedures can have both positive and negative environmental impacts. Locally adapted seed varieties are often saved and used in traditional seed storage, which contributes to the preservation of biodiversity. This helps maintain a diverse range of plant species and genetic resources (Nazarea, 2005). Conventional storage practices, such as the use of clay jars or simple containers, require minimal energy input compared to modern refrigerated storage (Mohamud et al., 2017). This results in a lower carbon footprint associated with the storage process. However, traditional seed storage methods may lack the sophisticated pest control measures and climate control found in modern facilities. Traditional storage approaches may not provide optimal conditions for long-term seed viability, making stored seeds more susceptible to damage from pests and diseases and potentially leading to crop losses. Traditional storage approaches may not provide optimal conditions for long-term seed viability, making stored seeds more susceptible to damage from pests and diseases and potentially leading to crop losses. According to Nadarajan et al. (2023), this is a common issue that can be addressed by implementing proper storage techniques. Exposure to fluctuating temperature and humidity can cause seeds to lose their germination ability more quickly, limiting their shelf life compared to seeds stored in controlled environments (Taylor, 2020). Storage methods that rely on ambient environmental conditions can become outdated and more vulnerable to the effects of climate change. Extreme weather events, such as floods or droughts, can negatively impact the quality and viability of stored seeds. Inefficient use of resources may also result from traditional storage methods (Maity et al., 2016). Improper storage conditions can lead to higher rates of spoilage, which may require farmers to use more seeds than necessary to compensate for losses. Therefore, it is essential to balance the positive and negative aspects of traditional seed storage methods (Kumar and Kalita, 2017). Integrating traditional knowledge with modern technologies, such as improved storage containers and pesticides, may reduce some of the negative environmental impacts while maintaining the benefits associated with traditional seed storage practices (Kumar and Kalita, 2017).

2.2. Global Food Security Concerns

Global food security refers to a situation where all people have access to enough, safe, and nutritionally adequate food to meet dietary needs and food preferences for active and healthy lives (Roetter and Keulen, 2007). With the world's population continuously growing, it is estimated that by 2050, there will be over 9 billion people. To meet the growing demand for food (McKenzie and Williams, 2015), the increase in population will put significant pressure on food production systems. Climate change poses a severe threat to global food security, as changes in temperature, precipitation patterns, and extreme weather events can affect crop yields, water availability, and the overall stability of agricultural systems. Farmers face challenges in planning and managing their crops due to unpredictable weather conditions (Kang et al., 2009). Water scarcity in many regions of the world poses a major challenge to food production as agriculture is a water-intensive activity. Competition for water resources between agriculture, industry, and urban areas can lead to water shortages, which in turn affect crop yields and food security (Rosegrant et al., 2009). The fertility of agricultural land can be reduced by soil erosion, deforestation, and other forms of land degradation. This loss of cultivable land makes it difficult to maintain agricultural productivity, leading to reduced food production. Additionally, the decline in biodiversity can impact ecosystems and reduce the resilience of agricultural systems (Altieri et al., 2015). Biodiverse systems can be more resistant to pests, diseases, and environmental stresses, which can contribute to stable food production. However, fluctuations in global commodity markets, energy prices, and geopolitical events can lead to volatility in food prices (Fan et al., 2021). High and unstable food prices can harm access to adequate and affordable food for vulnerable populations, which is often exacerbated by poverty and income inequality. Individuals with limited financial resources may face difficulties in accessing nutritious food, which can result in malnutrition and other health problems (Pollard and Booth, 2019). International trade policies, tariffs, and trade barriers can have an impact on the movement of food across borders. Unfavorable trade conditions can disrupt the availability of food in certain regions, affecting both local and global food security (Ingram, 2011). Production, distribution, and access to food can be disrupted by conflict, political instability, and social unrest, leading to food shortages and humanitarian crises (Bora et al., 2011). The adoption of modern agricultural technology, including improved seed, irrigation systems, and sustainable farming methods, differs around the world and has a significant impact on agricultural productivity (Khanna et al., 2011). and significantly impacts agricultural productivity (Khan et al., 2021). A comprehensive approach is needed to address global food security concerns, including sustainable agricultural practices, investments in research and technology, policy measures, international cooperation, and efforts to reduce poverty and inequality. This multi-faceted challenge requires coordinated action locally, nationally, and internationally (Nicolétis et al., 2019).

3. Traditional Seed Storage Methods

Farmers have been using traditional seed storage methods for centuries to preserve seed viability and quality for future planting (Singh et al., 2013). These methods have allowed farmers to maintain a diverse range of crops, as they are often simple and rely on local resources. Drying is one of the oldest and simplest methods of seed storage. The process reduces the moisture content of seeds to a level that reduces their susceptibility to microbial growth and enzymatic activities which may lead to spoilage (Abdul and Anderson, 1972). Seeds are usually spread out in a single layer and left to air dry in the sun or a well-ventilated area. To protect seeds from pests, moisture, and extreme temperatures, many traditional societies have built granaries or storage structures. These structures are commonly used to provide ventilation and protect against ground moisture. For instance, in Africa, raised floor granaries, and in parts of Asia, bamboo granaries are used (Suleiman and Rosentrater, 2022). In some regions, seeds are stored in clay pots or earthenware containers, which allow for some airflow, preventing the buildup of moisture inside the container. Clay can also help regulate temperature through its thermal properties. Breathable bags made from materials such as jute or cloth can be used to store seeds. These bags allow for air circulation, which reduces the risk of fungal growth. To prevent deterioration (Gough, 2020), it is important to store seeds in a cool, dry place. Some farmers store seeds in alternating layers of sand or ash to control moisture and provide insulation against temperature fluctuations. This method helps maintain seed quality (McDonald and Copeland, 2012). Many cultures use hand-woven baskets of natural fibers like straw or bamboo to store seeds. These baskets provide ventilation and are often raised to prevent damage from ground moisture and pests (Kitinoja and Kader, 2002). In certain cultures, seeds are exposed to smoke before storage, which is believed to have fungicidal properties, protecting seeds from microbial attack (Gupta and Kumar 2020). In root and tuber crops, smoke treatment is particularly common. Traditional seed storage also entails selecting and saving seeds from the healthiest and most robust plants. However, there is a need for more research on how to improve the quality of seeds and how to use them more effectively (Govindaraj et al., 2016) for example, to improve pest and disease resistance, and to improve the quality of seeds that are suitable for use in the food chain. It is important to note that while these traditional methods have been effective for many communities over generations, some may not provide the same level of protection as modern seed storage technologies. Modern seed banks and storage facilities often use controlled conditions, low temperatures, and special containers to prolong the survival of seeds (Chin et al., 2012). Yet traditional methods remain of value, particularly in regions where access to modern storage facilities is limited.

3.1. Cold Storage

Cold storage is a technique for storing seeds at low temperatures to maintain their viability and Vigor for future use. Seed storage experiments (SSE) include the storage of seeds under specific temperature and moisture conditions, which can provide useful information (De Vitis et al., 2020). Cold storage performance is dependent on storage conditions, seed origin, and seed dormant type (Vasques et al., 2014). Research has demonstrated that storing seeds in cool, anoxic, or low-oxygen conditions can increase their longevity (Trusiak et al., 2022). Various cold storage techniques exist, such as storing seeds under controlled conditions of relative humidity (RH) and temperature, moist cold storage with temperature control, and cold storage technology with dehumidifiers. Standard storage methods are suitable for conserving seed-associated bacterial micro-biome (Chandel et al., 2021), while cold storage technology is expensive and should be reserved for storing low-volume, high-value seeds (Dadlani et al., 2023).

3.2. Drying and Desiccation

To maintain seed viability and longevity, drying, and desiccation are important seed storage techniques. To tolerate freezing, increase storage life, prevent pest and pathogen attacks, and postpone germination (Nadarajan et al., 2023), seeds should be dried to approximately 15% equilibrium relative humidity (eRH) before long-term storage. Silica gel, charcoal, and seeds such as rice or maize are effective desiccants. Drying seeds can be achieved using salts in a desiccator, which is a more precise method than using silica gel (Hay et al., 2023). Silica gel is recommended as the drying agent for seeds to be stored at room temperature, while calcium chloride is recommended for seeds to be refrigerated or frozen. To prevent moisture condensation on the seeds, allow them to reach room temperature before opening the storage container when stored in a freezer or refrigerator (Justice and Bass, 1978).

3.3. Chemical Treatments

To maintain seed viability and control storage grain fungi, chemical treatments such as fungicides can be used. Liquid seed treatments are widely used for most crops because of their uniform application, low cost, and lack of additional energy required for drying (Frandoloso et al., 2018). Long-term seed storage involves the preservation of seeds at very low moisture content and low temperatures in hermetically sealed containers, with the longest-term storage being in canisters of liquid nitrogen (Afzal et al., 2017). Physical methods, such as electromagnetic waves, magnetic fields, ultrasounds, and ionizing radiations, can provide seed revitalization with several advantages over traditional chemical treatments, including reduced use of fertilizers and reduced contamination of raw materials produced on the farm (Araújo et al., 2016).

3.4. Limitations and Drawbacks

Traditional techniques for storing seeds have limitations and drawbacks, particularly regarding energy consumption and genetic degradation over time. Preserving genetic diversity through seed storage presents challenges. Energy inputs are often required to maintain appropriate storage conditions. This section covers the energy required for temperature and humidity control, which can be significant, particularly for large-scale storage facilities. Traditional storage structures may rely on natural cooling and ventilation, but in warm and humid environments, this can be counterproductive, resulting in increased energy consumption (Afzal et al., 2017). Conventional seed storage techniques have a high energy consumption, which contributes to the environmental footprint of seed conservation efforts. To address these issues, alternative seed storage techniques should be explored. Additionally, genetic degradation is a significant drawback of these techniques. The longevity of stored seeds is influenced by factors such as moisture content and temperature, and genetic degradation can occur over time due to suboptimal storage conditions (Kameswara et al., 2017). For example, recalcitrant seeds, which do not tolerate conventional storage conditions well, can suffer from mechanical damage, metabolism-induced damage, and macromolecular deterioration, resulting in genetic degradation (Trusiak et al., 2022). Furthermore, certain seeds, such as sesame seeds, are susceptible to genetic degradation during storage due to their high oil content and fast cellular respiration. Therefore, advanced storage technologies are necessary to mitigate these effects (Alemayehu et al., 2023).

4. Emerging Sustainable Seed Storage Technologies

4.1. Cryopreservation

Cryopreservation is a viable technology for the long-term conservation of genetic material from various types of plants, including those with recalcitrant seeds (Walters and Pence, 2021). Cryopreservation is a safe and efficient alternative method for the ex-situ conservation of germplasm. It helps overcome several limitations of storage by conventional methods such as seed banks and clonal propagation (Benelli, 2021). This technique involves the storage of biological samples in tanks filled with liquid nitrogen, making it the most feasible technique for the long-term preservation of genetic material from different categories of plants (Kaviani et al., 2022). Cryopreservation ensures sample viability after thawing and allows for indefinite storage. Its advantages include reduced in vitro culture costs, required space, contamination risk, and operator errors. Cryopreservation is a safe strategy for long-term conservation and a backup to field collections (Kaviani et al., 2022; Walters and Pence, 2021). Establishing efficient cryogenic procedures is a challenging task that requires consideration of several factors. The stability and homogeneity of stored samples are of utmost importance when it comes to the impact of cryopreservation. It is essential to develop simple, reliable, and cost-effective methods, and sharing know-how can accelerate progress (Benelli, 2021; Kaviani et al., 2022). Scientists within the Millennium Seed Bank Partnership are researching alternative methods for banking endangered species that cannot undergo standard seed banking procedures. One such technique is cryopreservation, which involves rapidly drying seeds or seed parts and then freezing them using liquid nitrogen. These new techniques can help reduce the impact of collection on the population's continued survival (Kew, 2022).

4.2. Innovative Drying Techniques

4.2.1 Low-energy Drying Methods

Emerging sustainable seed storage technologies, such as innovative drying techniques, low-energy drying methods, and vacuum-sealing, are essential for preserving seed viability and quality (Dadlani et al., 2023). These technologies play an important role in ensuring food security and sustainable agriculture by extending the storage life of seeds and increasing their viability. Several research articles highlight their importance for sustainable agriculture (Pandey and Pandey, 2023). Innovative drying techniques, such as low-energy methods, are necessary for reducing seed moisture to levels suitable for long-term storage. Trail et al. (2021) found that storing seeds in dry, cool, and low-oxygen conditions slows seed metabolism, prolonging storage life. The significance of low-cost technologies for drying seeds is highlighted, particularly in tropical environments where high humidity and heat pose significant challenges to seed storage.

4.2.2 Vacuum-Sealing and Controlled Atmosphere Storage

Vacuum sealing and controlled atmosphere storage are key components of sustainable seed storage. These methods help maintain seed quality by creating an environment that minimizes oxygen and moisture levels. The use of desiccants and vacuum sealing has also been proposed to maintain seed quality in climate-controlled seed banks (Trail et al., 2021).

4.2.3 Nanopriming

Nanopriming is a seed-priming technology that utilizes nanotechnology to improve seed germination, growth, and yield (Nile et al., 2022). The potential of nanoparticles in seed treatment and enhancement for sustainable farming has been demonstrated in studies, emphasizing the role of nanotechnology in seed technology (Eevera et al., 2023; Nile et al., 2022).

4.3. Natural Seed Coatings (Encapsulation)

Seed coating technology is a sustainable and innovative approach to improving seed quality and crop performance (Javed et al., 2022; Afzal et al., 2020). Natural seed coatings, which use natural materials for seed encapsulation, are one of the emerging sustainable seed storage technologies. They offer several benefits, including improved seed germination, enhanced nutrient uptake, and overall plant growth (Sujata et al., 2023). The passage discusses the benefits of natural seed coatings, which can enhance seed germination and nutrient uptake by providing a reservoir of beneficial microbes. These coatings can be made from various biodegradable and environmentally friendly materials, such as chitosan, alginate, and gelatin (Afzal et al., 2020). Chitosan is a natural polymer formed from chitin, which is found in the exoskeleton of crustaceans. Studies have shown that it can improve the germination of seeds, increase the growth of plants, and improve their resistance to biotic and abiotic stresses (Afzal et al., 2020). Alginate, a natural polymer derived from brown seaweed, has been used as a seed coating material to improve the germination of seeds and to increase the uptake of nutrients. Gelatin, a protein obtained from collagen, is found in animal bones and skin, been used as a seed-coating material to improve seed germination and enhance plant growth. In sustainable seed storage, natural seed coatings have several applications. It can protect seeds from environmental stressors like dryness, salinization, and thermal extremes (Madsen et al. 2016) Additionally, they can improve seed quality and crop performance by enhancing seed germination, nutrient uptake, and overall plant growth (Javed et al., 2022; Afzal et al., 2020; Sujata et al., 2023). Furthermore, natural seed coatings can be utilized to administer bioactive compounds, such as plant growth regulators, fungicides, and insecticides, to both the seed and the developing plant (Afzal et al., 2020). Using natural materials to encapsulate seeds, these coatings are an emerging sustainable seed storage technology. It provides multiple advantages, including improved sprouting, increased nutritional intake, and overall plant growth. Natural seed coatings can be made from a variety of materials such as chitosan, alginate, and gelatin. They have numerous potential applications in sustainable storage, such as protecting seeds from environmental influences and delivering bioactive compounds to the seed and developing plant.

5. Role of Biotechnology in Sustainable Seed Storage

By improving the resistance of seeds to environmental stressors, biotechnology plays a key role in sustainable seed storage. For the conservation of plant genetic diversity, including economically important crops, and food security, seed storage is essential (Salgotra and Chauhan, 2023). Seeds are classified according to how they behave when stored:

orthodox and recalcitrant. Orthodox seeds can be stored for long periods without any significant loss of vitality, whereas recalcitrant seeds are more susceptible to storage conditions and require special storage methods (Shvachko et al., 2020).

5.1 Genetic Modification for Enhanced Seed Resilience

5.1.1 Traits Promoting Longer Seed Viability

Seed viability is a critical factor that affects the potential for seed regeneration and is essential for ensuring a productive agricultural yield (Mendoza et al., 2022). Various methods, such as germination testing, the electrical conductivity (EC) method, and the staining method, have been used to determine seed viability (Wang et al., 2023). However, seed viability is influenced by its degree of aging and genetic factors. one study has proposed methods for evaluating maize seed viability. Fan et al. (2023) proposed a reliable and effective method using hyperspectral imaging technology and a multi-scale 3D convolutional neural network. This method provides valuable references for agricultural applications. Wang et al. (2023) developed a rapid and quantitative method using 2,3,5-Triphenyl Tetrazolium Chloride (TTC) to determine seed viability. This method efficiently measures seed viability with different aging degrees and is sensitive. In the context of orchid seeds, the testing of seed viability is an essential tool for the conservation of the seeds (Pradhan et al., 2002). Orchid seeds are ideal resources for seed banking due to their minute size, dust-like seeds, and weight, which enables large-volume storage without the need for large facilities. However, over time, all seed collections gradually age and decline in viability.

5.1.2 Resistance to Environmental Stressors

Seed storage presents a significant challenge due to the accumulation of free radicals, specifically reactive oxygen species (ROS), which can cause genome instability and loss of viability. Biotechnology offers a solution to this challenge by developing seed storage proteins (SSPs) and seed coat compounds (SCCs) that improve seed resistance to oxidative stress during storage (Shvachko and Khlestkina, 2020). For instance, sesame's main seed storage proteins, the 2S albumin, and the 7S and 11S globulins, underwent purification and proteolysis with pepsin in a study conducted by Orruño and Morgan (2011). They comprehend the molecular genetic foundations of seed resistance to oxidative stress during storage. In another study, seed storage proteins and seed coat compounds linked to tolerance to *C. maculatus*, a storage pest, were evaluated. They aimed to identify SSPs and SCCs that could be used to develop more effective seed storage strategies (Amusa et al., 2023).

5.2 Molecular Approaches to Seed Longevity

5.2.1 Genetic Basis of Seed Aging

Seed aging is the gradual degradation of seed quality with time, leading to a reduction in viability and vigor. This process is influenced by various internal and external factors and often involves genetic changes (Chhabra and Singh, 2019). To understand the genetic basis of seed aging, it is necessary to explore the molecular and genetic mechanisms that contribute to seed deterioration over time (Ventura et al., 2012). Seeds from different plant species, and even different cultivars within a species, can be differentially susceptible to aging (Long et al., 2015). Genetic variation is a critical factor in determining how seeds respond to aging conditions. During seed aging, changes in gene expression patterns can occur, leading to alterations in biochemical pathways and metabolic processes (Kurek et al., 2019). Understanding these changes can provide insights into the molecular events associated with aging. Aging can cause DNA damage in seeds. Understanding how seeds cope with and repair DNA damage that accumulates over time can be achieved by studying the genes involved in DNA repair mechanisms (Waterworth et al., 2016). Seed aging is often associated with increased oxidative stress, which can damage cellular components. Genes that encode enzymes such as superoxide dismutase and catalase play a crucial role in protecting seeds from oxidative damage (Adetunji et al., 2021). Investigating genes involved in protein quality control, such as chaperones and proteases, can provide insights into the mechanisms of seed aging, as proteins are essential for seed viability, and their degradation or misfolding can contribute to aging (Chen et al., 2013). Seed aging is influenced by various metabolic pathways, including those related to lipid metabolism, carbohydrate metabolism, and energy production. To unravel the genetic basis of aging, it is important to study the genes involved in these pathways. Additionally, plant hormones, such as abscisic acid (ABA) and gibberellins, play a role in seed development and aging (Macovei et al., 2017). Therefore, genes involved in hormonal pathways may also influence seed aging by regulating physiological processes. Epigenetic modifications, such as DNA methylation and histone modifications, can impact gene expression in seed aging (Jhanji et al., 2024). It is important to understand the epigenetic regulation of genes involved in aging processes to unravel the genetic basis. Researchers use a variety of techniques, which include molecular biology, genomics, transcriptomics, and bioinformatics, to investigate the genetic basis of seed aging. Identifying key genes and pathways is crucial for developing strategies to improve seed longevity and seed storage practices for agricultural and conservation practices (Dwivedi et al., 2021).

5.2.2. Targeted Interventions for Prolonged Storage

Biotechnology provides targeted interventions to improve the long-term storage of seeds and ensure their viability and vigor over long periods (Salgotra et al., 2019). Key approaches include bioactive compounds, such as antioxidants and desiccants, which can be applied through seed coating or encapsulation to protect seeds from oxidative damage and dehydration during storage (Siddiqui et al., 2023). Additionally, biodegradable polymer coatings can serve as a physical barrier to maintain seed moisture content and prevent external factors from impacting seed quality (Beikzadeh et al., 2020). Incorporating genes that confer resistance to environmental stresses such as drought and cold improves the ability of seeds to withstand severe conditions during storage (Howarth and Ougham, 1993). Additionally, incorporating genes for resistance to seed-borne pathogens can help protect against infections that can affect seed quality while in storage (Muthii, 2014). Encapsulating somatic embryos with nutrient-rich gel matrices or artificial coatings enables extended storage of embryonic plants, developing synthetic seeds. This provides protection and sustenance to the plant. The technique was discussed by Sharma et al. (2013). Cryopreservation is a method of storing seeds at ultra-low temperatures, typically below -196°C, to minimize metabolic activity and prevent aging. This technique is particularly effective for long-term storage of a wide range of plant species (Funnekotter et al., 2017). Modifying metabolism to increase antioxidant production in seeds can reduce oxidative stress and preserve seed quality during storage (Adetunji et al., 2021). It is also possible that by introducing genes involved in the maintenance of telomeres, the longevity of stored seeds can be increased (Dhalaria et al., 2014). Silencing damaging genes: Development of seeds with extended storage potential by preventing the activation of aging-related processes through the use of RNAi technology to silence genes responsible for seed deterioration (Leri et al., 2020). Nanoparticle Coatings: Nanoparticulate and nanocomposite materials are used to coat seeds to provide increased protection against environmental factors, pathogens, and physical damage during storage. (Vega et al., 2023). DNA Barcoding and Digital Storage: DNA barcoding is a biotechnological tool used to digitally store genetic information, which ensures the preservation of seed characteristics. This approach facilitates the efficient identification and retrieval of seeds for future use (Karaca and Ince, 2019). These interventions demonstrate the various applications of biotechnology in seed storage, intending to preserve seed quality, viability, and genetic integrity over extended periods. This contributes to sustainable agriculture and biodiversity conservation.

6. Environmental Impacts and Economic Viability

Biotechnological seed storage can have both environmental and economic implications. Biotechnological techniques such as cryopreservation and gene banking can assist in the conservation of plant genetic diversity (Salgotra and Chauhan, 2023). Preservation of a diverse range of seeds helps to prevent the loss of valuable traits that may be crucial for adapting crops to changing environmental conditions (Pautasso et al., 2013). Biotechnology enables the long-term storage of seeds under controlled conditions, minimizing the need for extensive land use and reducing the environmental footprint associated with traditional storage methods (Brookes and Barfoot, 2012). Biotechnology seed storage can enable the development and conservation of improved crop varieties. This can lead to increased agricultural productivity, which in turn can have a positive impact on the economy by improving food security and supporting farmers' livelihoods (Rao, 2004). Though the initial costs of establishing biotech seed storage facilities can be high, the long-term benefits of reduced seed loss and better crop performance can result in cost savings for both farmers and the agricultural industry. Maintaining a diverse seed bank through the use of biotechnology can provide a valuable resource for researchers and breeders. This diversity could help develop improved trait crops, which could open up new markets and economic opportunities (Peres, 2016). The overall impact of biotech seed saving will depend on many factors, including the specific techniques used, the types of crops involved, and the regulatory framework in place. In addition, ethical, social, and cultural considerations should be taken into account to ensure that benefits are shared equitably and potential risks are minimized.

6.1. Comparative Analysis of Sustainability

6.1.1 Energy Efficiency

Especially in regions with extreme climates, traditional seed storage facilities can consume significant amounts of energy for temperature control. To reduce energy consumption, implementing energy-efficient climate-controlled storage, such as insulated facilities and advanced HVAC systems, is recommended (Bogucz, 2017). Additionally, many seed storage facilities rely on non-renewable energy sources. The use of renewable energy sources, such as solar or wind power, can significantly reduce the environmental footprint. Inefficient lighting systems can contribute to energy waste. To decrease energy consumption, it is recommended to use energy-efficient LED lighting or natural light through well-designed storage facilities (Chel and Kaushik, 2011). Additionally, traditional facilities may lack systems for energy recovery, but Energy can be captured and reused through the implementation of energy recovery systems, such as heat exchangers, thereby improving overall efficiency.

6.1.2. Reduction in Chemical Usage

Integrated pest management (IPM) strategies, such as biological controls and resistant seed varieties, can reduce reliance on chemical inputs commonly used for pest and pathogen control. It is important to note that chemical pesticides and fumigants should only be used when necessary. Integrated pest management (IPM) strategies, such as biological controls and resistant seed varieties, can reduce reliance on chemical inputs commonly used for pest and pathogen control. Chemical seed treatments are commonly used to prevent diseases. The development and adoption of non-chemical seed treatments, such as biopesticides or seed coatings with beneficial micro-organisms, can reduce the use of chemicals (Lamichhane et al., 2022). In addition, ensuring adequate storage conditions can also prevent the need for chemical preservatives. Hermetically sealed storage systems can create an inhospitable environment for pests and disease agents, thus reducing the need for chemical preservatives (Harrington and Kozlowski, 1972). Overreliance on chemicals can conceal the underlying seed quality problems. Periodic screening of seed quality using non-chemical methods can help identify and address problems without resorting to unnecessary chemical intervention (Deguine et al., 2023).

6.1.3. Cost-Effectiveness of Sustainable Seed Storage Methods

Conventional seed storage practices often include energy-intensive processes such as refrigeration. Sustainable practices such as on-farm seed storage or low-energy technologies such as CoolBot-controlled cold rooms can reduce energy consumption and costs (Zhu et al., 2020). There can be significant infrastructure costs associated with building and maintaining seed storage facilities. However, investing in sustainable and durable structures can result in long-term savings. Passive cooling systems and well-designed facilities are examples of green technologies that can reduce ongoing operational expenses. Sustainable seed storage methods, such as natural ventilation or hermetic storage bags, may require lower maintenance costs over time (Shaw et al., 2020). Erickson and Halford (2020) suggest that sustainable seed storage methods adapted to local climates can be more cost-effective. For example, climate-responsive structures can reduce the need for energy-intensive climate control systems. It is crucial to educate farmers and seed bank personnel about sustainable seed storage practices. Although training may entail initial costs, the long-term benefits of reduced losses and improved seed survival may exceed this cost (Hlatshwayo et al., 2021).

6.1.4. Long-Term Benefits for Farmers and Seed Banks

By ensuring that farmers have access to a wide range of seeds, sustainable seed storage methods help to maintain genetic diversity. This diversity is essential to adapt to changing environmental and pest conditions, thereby increasing long-term resistance (Pathirana and Carimi, 2022). Effective seed storage methods help minimize seed losses due to pests, diseases, and environmental factors. Sustainable seed storage practices can directly benefit farmers by ensuring a more reliable seed supply, reducing the need for frequent seed replenishment (Maity et al., 2023). Quality seeds stored using sustainable methods can lead to higher crop yields, resulting in increased productivity and better economic returns for farmers. This, in turn, contributes to long-term food security and economic stability (Albahri et al., 2023). Community-based approaches are often employed in sustainable seed storage practices. Enabling local communities to manage their seed banks promotes self-sufficiency and resilience, reducing reliance on external sources for seeds (Meixner, 2021). Sustainable seed storage methods that take into account climate resilience can assist farmers in adapting to changing climate conditions. This adaptability is crucial for long-term agricultural sustainability and economic viability (Chami et al., 2020). The relationship between the cost-effectiveness of sustainable seed storage methods and the long-term benefits for farmers and seed banks is intertwined. While initial costs may be incurred, economic profitability is often realized over time through increased resilience, reduced losses, and improved agricultural results. In addition to the economic benefits, sustainable seed storage methods promote environmental conservation and the overall well-being of the farming community (Deguine et al., 2002).

7. Challenges and Future Directions

7.1. Technological Barriers

In many regions, particularly in developing countries, there is a lack of the necessary infrastructure and tools for advanced seed storage technologies. This includes poorly equipped seed banks, cold storage facilities, and monitoring systems (Khan and Shrestha, 2020). The implementation and maintenance of advanced seed storage technologies can be expensive, making it challenging for some regions to adopt these methods. High costs could impede the widespread adoption of technologies such as cryopreservation or automated seed monitoring systems (Walters and Pence, 2021). Adequate training is key to the effective use of advanced seed storage technologies. The lack of skilled personnel in handling and maintenance of these technologies can be a significant barrier. Seed bank staff requires capacity-building programs to learn how to properly use and maintain new storage methods (Vernooy et al., 2017).

7.2. Resistance to Biotechnological Approaches

There may be some members of the public who have reservations or concerns about the use of biotechnological approaches in the conservation of seeds. Problems associated with GMOs and GM seeds may result in resistance and regulatory issues (Ramjoue, 2009). The adoption of biotechnological approaches in seed storage may be hindered by stringent regulations and policies. The establishment of clear and internationally accepted guidelines that address safety concerns is essential to facilitate the adoption of innovative biotechnology methods (Anderson, 2010). Resistance to genetically modified seeds may also arise from ethical and environmental concerns, such as the unintended consequences or potential impact on biodiversity. Overcoming this resistance requires addressing these concerns through rigorous testing, transparent communication, and ethical considerations (Pretty, 2001). Additionally, the lack of global standards poses a challenge. The lack of universally accepted standards for seed storage practices can hinder widespread adoption. To ensure consistency and compatibility across different regions and organizations, it is important to establish international collaboration and develop standardized protocols (Mulesa et al., 2021). Moreover, limited sharing of knowledge and experiences between different seed banks and research institutions can impede progress. Teixido et al. (2017) suggest that open communication and collaboration can facilitate the propagation of best practices and lessons learned. Climate change is creating uncertainty and challenging the conservation of seeds. The effectiveness of traditional and modern storage methods may be affected by changes in temperature and humidity patterns. Thus, research and adaptation of storage technologies to changing climate conditions are necessary (Singh et al., 2015). Integration with local agricultural practices is necessary for the successful adoption of seed storage technologies. To ensure that storage solutions align with the needs and preferences of farmers, it is essential to bridge the gap between scientific advancements and traditional farming methods (Kassie et al., 2013). Overcoming these challenges will require collaboration between governments, research institutions, NGOs, and the private sector. To promote the widespread adoption of advanced seed-storage technologies, continued innovation, education, and outreach programs are also essential.

7.3. Prospects for the Future

Future research on advances in biotechnology has the potential to improve the viability and durability of stored seeds by understanding the genetic and biochemical factors contributing to seed degradation and developing strategies to reduce these factors (Sudhakar et al., 2020). In addition, genetic engineering can help develop seeds that are more resistant to environmental stresses such as drought, salinity, and extreme heat. Biotechnology has the potential to assist in crop cultivation in challenging climates, enabling farmers to adapt to changing environmental conditions (Trono and Pecchioni, 2022). It can also be used to produce seeds with improved pathogen and pest resistance, reducing the need for chemical pesticides and promoting more sustainable agricultural practices (Jauhar, 2006). Collaborative efforts between countries and organizations are underway to establish seed banks and vaults for the long-term storage of diverse plant genetic resources. Initiatives like the Svalbard Global Seed Vault in Norway serve as a global backup for seed diversity (Westengen et al., 2018). To drive innovation in seed storage technologies, collaboration between governments, research institutions, and private companies is essential. Through public-private partnerships, resources and expertise can be leveraged to speed up the development and implementation of new biotechnological solutions (Loch and Boyce, 2003). The use of CRISPR technology, including CRISPR-Cas9 and other genome editing tools, provides precise methods for modifying specific genes in seeds. This can be used to improve traits such as yield, nutritional content, and disease resistance, thus opening up new opportunities for the improvement of crop plants (Rasheed et al., 2022).

8. Conclusion

This review presents a thorough analysis of current developments and trends in seed storage technology, with a focus on sustainable methods that might strengthen global food security. We hope to add to the continuing conversation about the critical role that seed storage plays in safeguarding the future of agriculture and guaranteeing a resilient and sustainable global food supply by looking at the transition from conventional practices to state-of-the-art technologies and the incorporation of sustainability principles.

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