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Moisture Management in Seed Storage for Ensuring Seed Longevity and Quality Preservation

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Seed moisture content is the most critical factor determining seed longevity during storage. Since seeds are hygroscopic in nature, they constantly exchange moisture with their surroundings. Even little increases in moisture content accelerate metabolic and deteriorative processes, which reduces their vigour and viability. The physiological basis of moisture-mediated seed aging, the connection between moisture content and seed longevity, the storage behaviour of orthodox, intermediate and resistant seeds, techniques for determining moisture content and useful moisture management methods are all covered in this section. Overall, maintaining optimum seed moisture content together with appropriate storage temperature is essential for preserving seed quality, extending storage life, and ensuring the effective conservation of plant genetic resources.

Keywords: Hygroscopicity, Seed ageing, Desiccation tolerance, Physiological deterioration

Introduction

Seeds are living but metabolically inactive structures that require maintenance of cellular integrity throughout the period from harvest to planting or use. Many factors can influence this period, but moisture content and temperature, with moisture being generally more influential, are the most critical (Whitehouse *et al.*, 2017). Seed moisture content (SMC) refers to the amount of moisture or water present in the seed and usually expressed as a percentage of fresh weight (Siswanti *et al.*, 2021). Although it is a characteristic of the seed, it is determined by the balance between the moisture in the air (relative humidity) and that in the seed because seeds are hygroscopic and equilibrate with their surrounding environment (Whitehouse *et al.*, 2017). Understanding the role of moisture in seed deterioration forms the basis for developing appropriate procedures for drying, packaging, and storage. These procedures will depend on factors such as the characteristics of the seed, the length of time the seed is to be stored, and the resources like labour or equipment available to the grower, commercial seed producer, or genebank (Corbineau, 2024).

The Physiological Basis of Seed Deterioration by Moisture

The degradation of seeds during storage is significantly influenced by water. Seeds continue to be metabolically active at high moisture concentrations, with continuous respiration and enzymatic activity using up stored food reserves. This encourages the growth of storage fungi and insect infestation while producing heat and carbon dioxide (Ranganathan and Groot, 2023). Vertucci and Roos (1990) showed that the equilibrium relative humidity and seed water content are closely related and can be separated into different hydration zones, each of which is linked to particular deteriorative processes. These processes range from minor physical changes at low moisture levels to hydrolytic and oxidative damage at higher moisture levels.

The cytoplasm goes into a stable glassy condition when seeds are dried to the optimum moisture levels, which significantly limits molecular mobility and slows the biochemical processes that cause seed aging and germination loss (Ranganathan and Groot, 2023). Therefore, one of the best ways to extend seed longevity is to lower seed moisture content within species-specific limits. Excessive drying beyond the ideal moisture level does not offer any further storage advantages and may even hasten deterioration because of altered lipid structure and membrane characteristics, especially in oil-rich seeds. Different species have different optimum moisture contents for maximal storage life, which are mostly influenced by variations in the lipid composition of seeds and their water-sorption properties (Choudhury and Bordolui, 2023).

Classification of Seeds According to Storability

Depending upon storability and desiccation tolerance seeds are classified into three categories (Whitehouse *et al.,* 2017) and they are:

- **Orthodox seeds:** These seeds can be safely dried to extremely low moisture contents (usually below 5–7%) without losing viability since they are highly desiccation tolerant. These seeds are ideal for long-term conservation in seed banks since they can be stored at low or below-freezing temperatures for extended periods of time. This group includes the majority of vegetable crops, oilseeds, pulses, and cereals.
- **Recalcitrant seeds:** These seeds usually cannot be dried below a moisture level of 30% to 50%, and are highly susceptible to desiccation and cannot tolerate drying. They are susceptible to low temperature storage and quickly lose viability when dried below a species-specific critical moisture level. As a result, conventional dry and cold storage techniques are inappropriate for these seeds, creating major challenges to their long-term preservation. The seeds of many tropical tree species like mango, jackfruit, cocoa etc are recalcitrant.
- **Intermediate seeds:** Between orthodox and recalcitrant seeds, intermediate seeds exhibit storage traits. They are susceptible to freezing temperatures and get damaged by extreme desiccation, but they may withstand partial drying to moderate moisture levels. Their storage life is intermediate but is less than that of orthodox seeds and can be kept longer under properly regulated conditions than recalcitrant seeds. These seeds can be dried up to 7% to 15% moisture content. Seeds of coffee, neem, citrus, papaya etc are considered as intermediate seeds.

Influence of Seed Moisture Content on Seed Longevity

- **Harrington's Thumb Rule**

One of the most widely accepted practical guidelines describing the relationship between seed moisture content and longevity was developed by James F. Harrington of the University of California, Davis. Based on his pioneering research on seed storage and moisture relations, Harrington proposed two empirical rules that continue to guide seed storage practices. The first states that, within a seed moisture content range of approximately 4–14%, the storage life of orthodox seeds roughly doubles for every 1% reduction in seed moisture content. The second states that, within a temperature range of 0–50°C, seed longevity approximately doubles for every 5°C decrease in storage temperature. In addition, Harrington proposed the "100 Rule", which suggests that for short- to medium-term storage, the sum of the storage temperature (°F) and the relative humidity (%) should not exceed 100, with temperature contributing no more than half of this value (Harrington and Kozlowski, 1972). These rules continue to be widely used because they offer a clear and reliable framework for estimating seed longevity in many orthodox species, despite the fact that they are empirical and only applicable within certain moisture and temperature limits. Lowering seed moisture content from roughly 20% to 5% reduced the respiratory carbon dioxide production of conifer seeds by almost 1,000 times, demonstrating the significant impact of moisture content on seed survival (Willan, 1984; Thapliyal *et al.*, 2025). This significant reduction in metabolic activity emphasizes how important moisture management is to reducing seed aging and extending storage life.

- **The Ellis and Roberts Seed Viability Equation**

The widely recognized Ellis-Roberts seed viability equation was established by E. H. Roberts and R. H. Ellis. It is a quantitative model that uses species-specific constants to predict seed lifetime as a function of temperature, moisture content, and duration of storage. In order to estimate the storage potential of orthodox seeds under various environmental conditions, this model has emerged to be an essential tool in seed science (Pirredda *et al.,* 2023). Subsequent studies examined the optimum moisture content required to maximize seed longevity. Vertucci and Roos (1990) proposed that the greatest longevity is achieved when seeds are in equilibrium with 19–27% relative humidity, whereas Ellis and Roberts reported that equilibrium with approximately 10–11% relative humidity provides the maximum benefit of desiccation (Ellis *et al*., 1991). These conflicting observations showed that while lowering seed moisture content consistently increases durability, the exact ideal moisture level varies per species and is dependent on seed composition, storage conditions and longevity evaluation methods. Therefore, figuring out the ideal moisture content for long-term storage continues to be a crucial topic of study for seed physiology.

Optimal Moisture Content Ranges and Genebank Standards

The intended storage duration and purpose determine the ideal seed moisture content. While the FAO/IPGRI Genebank Standards propose drying seeds to 3–7% moisture content and storing them at −18 to −20°C for long-term genebank conservation, most orthodox crop species are thought to be appropriate for normal storage at a moisture level of 4–8%. Under these circumstances, metabolic activity is reduced and seed longevity is increased. Standard drying techniques can be further enhanced, according to recent studies. For instance, a study by Hay *et al*. (2022) showed that, in comparison to the conventional low-temperature drying method, drying freshly harvested and metabolically active cowpea and soybean seeds at 40°C and 35% relative humidity for a few days prior to conventional equilibrium drying increased seed longevity in several accessions. These results imply that seed conservation practices will continue to change as seed physiology advances and that drying conditions right after harvest may have an impact on storage performance later on. Relatively laxer storage requirements are sufficient for active or working seed collections, which are meant for regular distribution rather than long-term conservation. Over the medium term, seed viability can be successfully maintained with moisture-proof storage and controlled relative humidity (about 25% RH at ≤30°C or 45% RH at ≤20°C). Long-term conservation facilities, on the other hand, usually keep seeds at low temperatures and moisture contents, such as about 5% moisture content and 8°C in medium-term storage facilities. Periodic viability monitoring is carried out to ascertain regeneration intervals and assure the preservation of genetic resources.

Measuring Seed Moisture Content

Reliable seed moisture content determination is necessary for accurate seed moisture management. For routine moisture assessment, the constant-temperature oven-drying method is recommended by the International Seed Testing Association (ISTA) as the standard reference procedure. The low constant-temperature method (103 ± 2°C for 17 ± 1 h) is recommended for most species, while the high constant-temperature method (130–133°C for 1–4 h, depending on the species) yields faster results with just a minor difference in accuracy. In order to limit moisture exchange, ISTA recommends duplicate samples weighing 4–5 g, little exposure of seeds to the surrounding air prior to weighing, and a maximum discrepancy of 0.2% between duplicate moisture determinations for the majority of species. Karl Fischer titration is widely used as a reference method to validate other moisture detection techniques and is regarded as the most accurate analytical method for determining seed moisture content. However, its regular application is limited by its expense and complexity. Electronic moisture meters, on the other hand, allow quick and easy measurements for commercial seed testing by estimating moisture content based on the electrical characteristics of seeds. However, to assure accuracy, these meters must be calibrated against the oven-drying procedure for each species. Research has repeatedly demonstrated that oven drying is still the most dependable technique, while electronic meters might be more inconsistent.

Techniques for Managing Seed Moisture

- **Controlled Drying and Storage Conditions**

Commercial and genebank storage facilities use refrigerated dehumidified rooms, desiccant-based drying cabinets, or drying over saturated salt solutions or silica gel in smaller-scale settings to control the relative humidity and temperature of the storage atmosphere. Storage rooms and containers must maintain stable conditions because seeds equilibrate with ambient relative humidity rather than maintaining a fixed moisture content indefinitely (Pedrosa *et al.*, 2024). Variations in humidity, such as those caused by poorly sealed buildings or seasonal climate swings, allow seeds to re-absorb moisture and negate the benefits of prior drying. To reduce temperature and humidity fluctuation inside seed storage chambers, facility design guidelines advise insulated, moisture-proof construction, sealed doors and windows, and shielding from direct sunlight.

- **Hermetic Storage and Moisture-Proof Packaging**

Hermetic (airtight) storage provides an efficient and cost-effective way to preserve seed moisture content in areas where mechanical dehumidification is difficult or costly. Hermetic storage suppresses insect pests and fungal growth by creating conditions that lower oxygen levels and raise carbon dioxide through seed respiration by blocking the interaction of moisture and gases with the surrounding environment (Khalid *et al*., 2026). One of the most popular hermetic storage solutions for grains and pulses is the Purdue Improved Crop Storage (PICS) bag, which consists of two high-density polyethylene liners contained within a woven outer bag. According to studies, seeds kept in PICS bags had higher viability, a more consistent moisture content, and substantially less insect damage than seeds kept in conventional bags. While safe storage of cereal seeds is often obtained at 12–13% moisture content (equilibrium relative humidity below 65%), hermetic storage can reduce post-harvest losses by up to 98% (Dadlani *et al*., 2023). Hermetic storage is a viable alternative for both short-term and long-term seed preservation, as recent study has shown that freshly harvested maize seeds with moisture contents up to 21% can be securely stored in hermetic bags for up to 21 days before complete drying.

- **Moisture Sorption Behaviour and Hysteresis**

Because of a phenomenon called sorption hysteresis, the link between seed moisture content and equilibrium relative humidity is not entirely reversible, making seed moisture management challenging (Rezaei *et al.*, 2024). For species like barley, lupin, buckwheat, wheat, and pea, research comparing seeds dried from a hydrated state (desorption) with seeds re-wetted from a dry state (adsorption) found that seeds that adsorb moisture after drying reach a different equilibrium moisture content and have greater subsequent longevity than seeds that desorb to the same relative humidity from a wetter starting point. Other species, like yellow mustard and oilseed rape, had minimal hysteresis effect unless they were dried to extremely low moisture content.

Conclusion

The best way to increase seed longevity and maintain seed quality is to lower and maintain ideal seed moisture content. From Harrington's empirical rules to the Ellis-Roberts viability equation and current hermetic storage technologies, decades of research have consistently shown that seeds kept in cool, dry, and stable conditions maintain their viability and vigour for significantly longer than those exposed to temperature and humidity fluctuations. However, different species have different ideal moisture levels depending on how they store themselves (orthodox, intermediate, or recalcitrant). Therefore, reducing post-harvest losses, increasing seed longevity, and guaranteeing the long-term conservation of plant genetic resources depend on precise moisture determination, suitable drying techniques, and efficient storage technologies.

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