Seed Storage and Longevity: Mechanism, Types and Management

21

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Abstract

About one-third of the food produced in the world is never consumed due to loss or waste, which adversely affects agricultural productivity and food security for the rising population. The primary cause of such losses is poor storage due to high seed moisture content at harvest and damp storage conditions. Thus, maintenance of seed quality during storage is imperative to the propagation of food plants as seed is the first link in the food chain and the ultimate symbol of food security. In storage, seeds are preserved under regulated environmental conditions to maintain their viability but initial seed quality and seed moisture contents are major contributing factors of seed longevity. The purpose of seed storage may vary from seasonal storage to long-term germplasm conservation. Seed deterioration during storage is an inevitable process and can be delayed by controlling different abiotic (relative humidity, temperature and oxygen) and biotic factors (insects, fungi and rodents) that affect viability. Rate of seed deterioration is accelerated with increased initial seed moisture content, temperature and relative humidity of the storage environment. In this chapter, we discuss possible mechanisms of seed deterioration various factors that are related to seed deterioration and management strategies for the preservation of seeds during storage.

Keywords

Seed quality · Seed deterioration · Orthodox seeds · Hermetic storage · Seed longevity

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21.1 Introduction

Maintenance of seed quality during storage is important for further propagation of food plants as seed is the first step in the food chain and the ultimate symbol of food security (Vanangamudi et al. 2017). Safeguarding seeds under regulated environmental conditions to maintain its viability for longer period of time is termed as seed storage (Willan 1986). In its simplest form, under storage, mature seeds are kept for a short duration to wait for the ideal environmental conditions that allows seed planting, its emergence and proper growth (Bonner 2008). The significance of seed storage was highlighted for the very first time when human started to domesticate plants.

Poor storage practices are the main reasons for huge storage losses (50–60%) in cereals worldwide (Kumar and Kalita 2017). Storage losses vary according to prevailing climatic conditions with 10% losses in temperate regions, whereas humid tropical regions face higher storage losses amounting to almost 50% (Wijayaratne et al. 2018). These estimates of storage losses are based on the quantity that is physically lost during storage while losses in seed quality far exceed these figures. Deterioration of seeds starts immediately after their detachment from the mother plants and ideal seed storage practices prolong seed viability by slowing down the deterioration process (Doijode 2006). The main objective behind seed storage of economically important crops is to ensure the availability of planting stock for the next growing season. Accumulation of carryover seed supplies of desired crops for several years is also one of the key purpose of seed storage to meet seed demands during periods of low production (FAO 2018). Advancement of plant breeding knowledge and genetic technologies has also highlighted the importance of seed storage for conservation of germplasm to be used in breeding program.

Normally, seeds are stored for a short period between collection and sowing in the next season to overwinter unfavourable weather conditions. Long-term storage for several years (up to 10 years) makes sure the availability of seeds in the absence of annual crops. Seed storage for germplasm conservation is done for 10 to more than 50 years. Different seed storage techniques have been adapted depending upon the purpose of storage. These include open storage in conventional jute and polypropylene sacs, cryopreservation, modified atmosphere storage, hermetic storage, conditioned storage and low temperature storage. The purpose of any storage technique is to reduce the deteriorative changes occurring within the seeds to prolong seed longevity. Lipid peroxidation due to free radicals, enzyme inactivation, degradation of cell membrane and DNA disintegration is the major cause of seed ageing (Murthy et al. 2003; McDonald 1999).

Storage duration and objectives of the storage provide guidelines needed to devise procedure and strategies of safe storage (Bonner 2008). Factors that influence seed quality during storage also have a major role in deciding storage procedures and strategies. The amount of seed and storage duration must be considered before establishing storage facilities to make it economical. Improper storage leads to the death of 90% seeds before the next growing season and is equally wasteful as it spoils all the efforts made during harvesting and collection process (Willan 1986).

This chapter covers seed storage behaviour, its deterioration mechanism and management strategies for preserving seed quality during storage.

21.2 Seed Storage Behaviour

Before going to storage, it is very important to remember that the seed is a miniature plant that cannot live indefinitely and will die after a certain storage period. There are two major classes of seeds based on their drying and storage behaviour i.e. orthodox and recalcitrant seeds (Roberts 1973). Orthodox seeds are desiccation tolerant and undergo maturation drying. They have long storage life and their longevity can be increased by reducing the moisture content and temperature of storage environment. Cereals and legume crops are mainly orthodox seeds. Contrary to orthodox seeds, recalcitrant seeds are sensitive to drying and freezing and have short storage life (FAO 2018). An intermediate category between orthodox and recalcitrant seeds has also been proposed (Ellis et al. 1990).

21.3 Factors Affecting Seed Quality during Storage

21.3.1 Factors Related to Seeds

Seeds are hygroscopic and absorb and desorb water depending upon external relative humidity. Variation in seed moisture at the same relative humidity level is due to difference in seed composition. Oily seeds have low moisture and storage life at the same relative humidity compared to starchy seeds (Copeland and McDonald 2001; McDonald 2007). Initial seed viability, seed moisture content, seed maturity, seed composition, seed size, mechanical damage and dormancy are factors that are related to seeds, and seed quality after any storage period is strongly linked with these factors.

21.3.1.1 Initial Seed Viability

Seeds with higher values of initial seed viability have more storage life or higher longevity after any storage period as compared to the seed lot having low initial viability. Germination test should be performed for every seed lot before taking it into storage to know about the expected storage life of seed. Sometimes, dormancy-breaking treatments are necessary for the freshly harvested seeds before their germination assessment. Seed lot longevity is highly associated with percentage of seeds that germinate in initial germination test, and it may vary from 50% to 90% for two seed lots of the same species. Storage of seed lot with 50% initial seed germination is wastage of storage space and resources, as this lot will lose its viability more quickly during storage than the seed lot having 90% initial viability. For short-term storage i.e. for few weeks or a couple of months, deterioration in seed quality is not a serious concern but for germplasm conservation, no seed lot should be accepted which has <85% initial viability depending upon the species or variety in question (Copeland and McDonald 2001).

21.3.1.2 Seed Moisture

Seed moisture content is the most important factor that affects seed longevity in storage. Seed is hygroscopic and absorbs moisture from the surrounding; so, any change in temperature and relative humidity affects its quality. This relationship between prevailing relative humidity and seed moisture content at a given temperature is known as seed moisture isotherm or absorption isotherm (Copeland and McDonald 2001). The importance of seed moisture content has been highlighted by Harrington who stated that in normal range of temperature and moisture, the storage life of seed could be doubled by each reduction in 1% seed moisture content (Harrington 1972). Seed quality is at the greatest risk at high moisture content in storage (Bewley et al. 2013). However, there is lack of awareness that moisture is the culprit for the low quality of seeds in developing countries. Rate of seed respiration increased when moisture content increases from 18% to 20%. Insect infestation is minimal below 8–9% moisture content. A non-dormant seed may germinate above 30% seed moisture content. Fungi cannot grow below 13% seed moisture content on starchy seeds and 7–8% in oily seeds which are in equilibrium with ambient RH value that nearly equals 68% (Bradford et al. 2018). Moisture contents of maize seed stored in conventional polypropylene bags increased due to higher ambient relative humidity, which resulted in poor seed germination and higher storage losses due to stored grain pests and aflatoxin contamination (Afzal et al. 2017). Seed moisture also mediates the seed mechanical damage by harvesting and threshing machinery, thus affecting the storage life of seeds.

21.3.1.3 Seed Maturity

Mature seeds have longer shelf life and longevity than seeds that were harvested before maturity. Immature orthodox seeds deteriorate faster and lose viability quickly compared to mature seeds under same storage conditions. Tomato seeds extracted from early ripe fruits have low vigour compared to mature seeds (Tetteh et al. 2018). Some tree seeds have the ability to complete maturation after they have been removed from the mother tree. Storage of immature cones of pines and other conifers for many weeks before seed extraction can enhance the longevity of the seeds (Bonner 1991).

Indeterminate pattern of flowering has been observed in many crop plants having most immature flower at the top of inflorescence and fully mature flower at the base. Also, younger branches have more immature flowers; thus, on the same plants, seeds of different maturity levels are found. This difference in seed maturity is reflected into seed storability. Some of the biochemical substances are accumulated into seeds during the final stages of seed maturity. These may be dormancy-inducing hormones or proteins related to desiccation tolerance. Seeds harvested before full maturity lack these essential compounds and perform poorly in storage.

Immature seeds are normally green in colour due to the presence of chlorophyll that is not degraded properly due to early harvest. A decrease in chlorophyll florescence is linked with increased germination of tomato seeds, indicating that mature seeds having less chlorophyll will have more germination potential and high quality (Jalink et al. 1999). Fractions of soybean seeds sorted on the bases of chlorophyll florescence showed a great difference in seed quality (Cicero et al. 2009). Seed fraction with low florescence values gave maximum percentage of normal seedlings, indicating that immature seeds having more chlorophyll florescence have low quality.

21.3.1.4 Seed Composition

Chemical composition is one of the most important factors for seed longevity. For example, oily seeds do not store well as compared to starchy seeds (Table 21.1). One can find support for this concept with the relatively poor storage performance of soybean (Shelar et al. 2008) and sunflower seeds (Abreu et al. 2013). Total seed oil compositional analysis is misleading because the oil contents in the embryo which is responsible for germination are more important for deciding the shelf life of seeds. *Glycine max* seeds have lower oil contents (21%) compared to *Brassica napus* seeds (36.4%), but the storage life of *Brassica napus* seeds is higher than that of *Glycine max* seeds. Seed storage life based of their oil contents and seed moisture contents can be predicted from seed viability equation (Royal Botanic Garden Kew 2019).

21.3.1.5 Seed Size

Seed size is one of the parameters of seed quality. Plant growth, yield and harvest efficiency is mostly related to seed size. Several studies have revealed the superiority of heavy, mature seeds over light, immature seeds in germination, vigour and yield

Table 21.1 Oil contents of some crop species and storage period after which they lose 50% germination at 25 °C and different seed moisture contents [9]

Crop species	Seed oil content (%)	Days to lose 50% germination at 14% SMC	Days to lose 50% germination at 8% SMC
Oryza sativa	2.2	100	1661
Cicer arietinum	4.1	251	3294
Zea mays	5	111	1737
Triticum aestivum	10	63	1674
Allium cepa	20	33	853
Glycine max	21	47	435
Brassica napus	36.40	41	516
Lactuca sativa	33.8	10	196
Gossypium hirsutum	38.4	108	1975
Linum usitatissimum	39.5	19	292
Brassica rapa	41.5	43	556
Arachis hypogaea	47.3	13	132
Sesamum indicum	50	34	322

95% initial germination; *SMC* seed moisture content tests. Relatively few exceptions have been noted. Larger seeds of finger millet have shown higher germination and vigour index after 8 months of storage as compared to smaller seeds (Lokesh et al. 2000). Seed quality of French bean with larger seed size (5 mm) was superior in terms of germination, seedling vigour index, seedling length, activity of α-amylase and dehydrogenase enzyme (Vishwanath et al. 2011). Bold wheat seeds of >2.2 mm give higher emergence rate and grain yield (Akinci et al. 2008). Larger soybean seeds give higher emergence and yield compared to smaller seeds (Morrison and Xue 2007).

21.3.1.6 Mechanical Damage

Seeds damaged mechanically by harvesting, threshing and cleaning equipment result in loss of viability. Mechanical damage does not affect seed quality immediately but for storage purpose, these effects are very serious and can cause much economic losses (McDonald 1985). Process of seed deterioration cannot be avoided and operates continuously. Mechanical damage to seeds, especially in dry season, can be very damaging as embryo is exposed to environmental factors (Linda 2019). Small damage to seed embryo is very harmful for seed life as compared to large damage to seeds that are not on embryonic tissue. Chances of mechanical damage exist more for seeds having a very thin or papery seed coat. Storage fungi and insects can easily attack damaged seeds as compared to non-damaged seeds, mainly by penetration into seeds through damaged seed coats. X-Ray analysis of sweet corn seeds showed that seeds with damaged embryonic axis resulted in abnormal seedlings and reduced germination (Gomes Junior and Cicero 2012). Inappropriate handling in cotton can damage the seed mechanically and thus accelerate seed deterioration during seed processing and storage (Jyoti and Malik 2013). The extent of mechanical damage mainly depends on seed moisture contents. With increase in seed moisture contents (>12%), seed coat is damaged during processing which exposes the embryo to ambient temperature and humidity, thus triggering seed deterioration (Black et al. 2006).

21.3.2 Factors Related to Storage Environment

Storage environment has a critical role in enhancing the shelf life of seed. The main objective is to minimize the rate of metabolic activities and to prevent seeds from attack of microorganisms and rodents. The reduced metabolic rate and respiratory activities help maintain the integrity of embryos by conserving food reserves within seeds. The following biotic and abiotic factors have major contribution in the longevity of seeds after harvest.

21.3.2.1 Relative Humidity and Storage Temperature

Temperature and relative humidity (RH) are related to each other and both factors collectively influence the seed moisture content (Copeland and McDonald 2001). Moisture-holding capacity of the air is influenced by temperature. Any change in temperature results in a change in air humidity, which ultimately affects the seed moisture content. This relation between temperature and RH is the base of seed storage principle which states that the aggregate of both temperature (°F) and RH should be <100 (Harrington 1973). High RH is the enemy for storage life of commodities such as cereal grains and oilseeds (Bradford et al. 2018). Seed storage at low RH is recommended as viability and vigour in seeds stored at high RH are significantly reduced (Suma et al. 2013). Temperature determines the speed of seed deterioration in both field and storehouse. Seed deterioration rate is accelerated if initial seed moisture content, temperature and RH of the storage environment is high (Goel et al. 2003). According to seed storage thumb rule, the life span of seeds can be doubled by a 10 °F reduction in temperature (Harrington 1972). Membrane integrity and structure are disrupted due to formation of intracellular ice crystals at low temperature and high (above 14%) seed moisture contents (Copeland and McDonald 2001). Okra seeds died completely at high temperature (45 °C) (Sahib 2014). Wheat seeds stored at a temperature of 40 °C and 45% RH lost 35–85% germination in 1 year, and losses in vigour was recorded to a range of 55–94%. Contrary to this, there were only 10–20% losses in germination and 15–22% vigour losses were recorded when wheat seeds were stored at 25 °C with 45% RH for a period of 1 year (Strelec et al. 2010).

21.3.2.2 Gases

Active oxygen species are produced from molecular oxygen during the transfer of electron through electron transport chain and are very damaging to the cellular structure (Bailly 2004). Free radicals cause peroxidation of lipids and other essential cellular constituents. Cellular lipid contents decreased due to series of harmful chemical reactions. Complete elimination of oxygen from the storage atmosphere seems beneficial to most dry orthodox seeds. However, it is indicated that some oxygen is required for recalcitrant seeds. Adequate ventilation supply (i.e. adequate oxygen) is essential for successful storage of recalcitrant seeds at relatively high moisture contents, as well as for storage of imbibed seeds of orthodox species (King and Roberts 1979).

Insect larvae can be killed using higher concentration of CO_2. For routine killing of insect larvae, orthodox seeds can be stored at modified atmosphere having more than 60% CO_2. Seed is safe from insects and fungal damage if it is dried at 8% seed moisture contents and stored in hermetic bags (Bakhtavar et al. 2019b) Rate of seed respiration and insect activities can be reduced by eliminating the available oxygen from the storage environment. The available oxygen of the storage environment can be replaced with nitrogen gas or CO_2 or by creating vacuum. Storage in hermetic Super Bags preserves seed quality by maintaining seed dryness and restricting oxygen entry into sealed bags (Bakhtavar et al. 2019a). Storage of seeds at high-pressure oxygen increased the rate of seed ageing during storage, suggesting a major role of oxygen in seed deterioration (Groot et al. 2012).

21.3.3 Biological Factors

21.3.3.1 Insects

Stored products are destroyed mainly by the direct feeding of insects. Seed embryo is the preferred food for some insect species. They feed on the embryo of seeds and cause complete loss of germination of damaged seeds. Insects feeding on the endosperm or food storage organs of seeds also cause huge quality and weight losses in stored grains. Mostly, insects prefer to attack the germ of seeds, as the germ is softer than the rest of the seed structures; thus, seed germination is lost readily (Bakhtavar et al. 2019b). Insect species including *Sitotroga cerealella* and *Rhizopertha dominca* are notorious for causing invisible losses to seed germination as their larvae feed on germ without leaving any sign of damage on the seeds (Prakash and Rao 1995). Stored grain pest attack on maize seeds resulted in 35% storage losses within 4 months of storage in conventional polypropylene bags (Afzal et al. 2017).

Seed germination is most sensitive to storage at high humidity/moisture. Fungal growth starts only at RH above 65% and insect activity is higher at 32–65% relative humidity (Fig. 21.1). Seed storage below 20–30% RH will reduce insect and fungal attack and thus, seed quality and longevity can be maintained (Bewley et al. 2013; Bradford et al. 2018).

21.3.3.2 Fungi

Invasion of storage fungi is promoted by several factors including storage temperature, grain moisture contents, RH and initial contamination in the storehouse. Mechanically damaged seeds are easily attacked by the microflora and thus are very prone to fungal invasion (Shelar et al. 2008). Occurrence of aflatoxin on grains

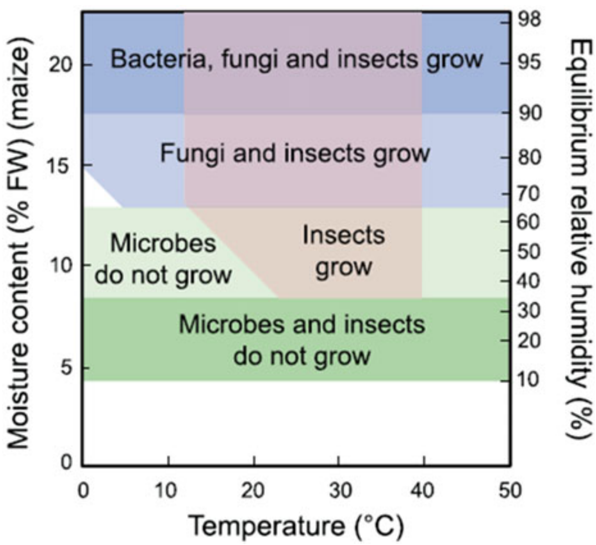

Fig. 21.1 Limits of seed moisture contests and temperature for storage of maize (adapted from Bradford et al. 2018)

can compound seed quality losses. Aflatoxin may develop due to storage at high moisture contents (Bewley et al. 2013). Consumption of grains contaminated with aflatoxin can impair the immune system as aflatoxin is a potent source of carcinogen and causes impaired uptake of nutrients present in food (Wu et al. 2014). Moulds responsible for the production of aflatoxin can grow on seeds only above 85% equilibrium RH (Abdel-Hadi et al. 2012). Such conditions are mostly prevailing in grain storehouses in developing countries (Ahsan et al. 2010).

21.3.3.3 Rodents

Thousands of tons of seeds are destroyed by rats, squirrels and other rodents each year. These losses are not only due to their feeding but most of the losses are by scattering and mixing of seed. Storage losses in cereals due to rodents, mainly rats, are >1%, while in developing countries, these losses are around 3–5% (IRRI 2019). Apart from storage losses, quality issue arises from rodent attack. Around 50 diseases have been reported in the world that is known to be transmitted to human by rodents. The best method to control rodents is to keep them isolated from the storage house. The most successful strategy to achieve this objective is to build such storehouses, which are free from rodent entryways like holes and cracks in the walls. Maintaining cleanliness in the storehouses is also a very good way to control the rodent's entry. Rodent's traps, fumigation and poison baits can also effectively control rodent infestation. Electric and modern zapper traps are getting very popular nowadays due to ease of use and its safety.

21.4 Mechanism of Seed Deterioration during Storage

Seeds have the unique ability to survive as living regenerative organisms, and like all other organisms, they cannot survive indefinitely and hence deteriorate and eventually die (Copeland and McDonald 2001). Basically, seed deterioration is linked with harmful process going on within seeds which make them vulnerable to environmental factors, thus reducing their storage life (Fig. 21.2). General concepts about seed deterioration are that seed deterioration is an unstoppable phenomenon and can be delayed by altering storage conditions. Moreover, seed deterioration is an irreversible process and rate of seed deterioration varies greatly among different species. Seed longevity parameters vary notably even for different accessions of indica rice (Lee et al. 2019).

Seed deterioration is a complex process and does not occur uniformly throughout seeds (Copeland and McDonald 2001). Seeds with high oil concentration, like cottonseeds, are more susceptible to deterioration, especially under poor storage conditions (Iqbal et al. 2002).

Degradation of cell membrane is the major cause of deteriorative changes occurring in seeds. This results in altered physical shapes and normal activities of cells. Increased free radical production and free fatty acid levels due to lipid peroxidation are the major causes of membrane disruption (Grilli et al. 1995). Lipid peroxidation due to free radicals, enzyme inactivation, degradation of cell membrane and DNA

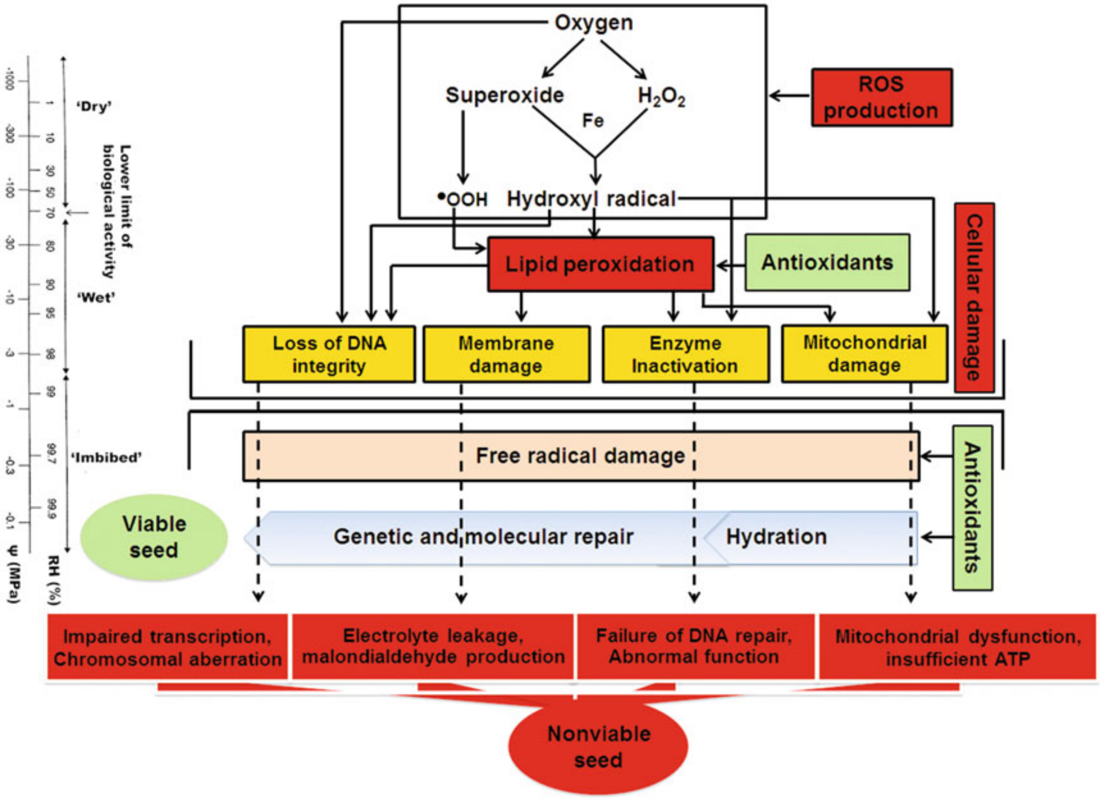

Fig. 21.2 Illustration of pathways and processes involved in seed deterioration. Graph at the left side represents the hydration level of seeds both in terms of water potential and equilibrium relative humidity; 70% RH is the lower limit of biological activity. (Adapted and modified from Osborne (1980), McDonald (1999), Walters et al. (2002), Bewley et al. (2013))

disintegration are the major causes of seed ageing (Murthy et al. 2003; McDonald 1999). Seed ageing is the result of enzyme degradation, which in turn is the result of altered macromolecular structure (Lehner et al. 2008; Bailly 2004). Electron transport chain operating in mitochondria is one of the major sources of ROS in the respiring seeds (Bailly 2004). Structural changes linked with oxidation are less fluidity of membrane, changes in DNA folding, reduced protein elasticity and augmented brittleness of cellular constituents (Walters et al. 2010).

Biochemical aspects of deterioration of seeds are chemical alterations which include degraded DNA, chromosomal aberrations and impaired protein synthesis due to RNA damage, altered membrane structure and reduced food reserves (Kibinza et al. 2006). Loss of protein functions induced by oxidation of protein is also one of the reasons of seed ageing (Rajjou et al. 2008).

Reduced contents of protein, total sugars, oil contents and increased reducing sugars and free fatty acids contents have been observed in aged seeds. Decreased oligosaccharides have been observed in deteriorated seeds, which are known to be involved in stabilizing membranes. In aged reddish seeds, the activity of peroxidase decreased as compared to fresh seeds (Scialabba et al. 2002). There was a sharp decline in the activity of peroxidase enzyme during sunflower ageing (Pallavi et al. 2003). Viability losses in sunflower seeds are linked with increased malondialdehyde content, confirming a strong association between lipid peroxidation and seed deterioration due to reduced efficiency of antioxidant defence system (Kibinza et al. 2006).

21.5 Types of Storage

21.5.1 Open Storage

Open storage has remained one of the basic and widely used storage methods and is still prevalent in developing countries. In traditional storage, maize cobs and sorghum panicles were tied in bundles and hanged with tree branches or post or tight lines within the house. This does not provide much protection against weather, fungus and insects. Seeds are stored in open containers, traditional porous bags, in piles and single layers of sacs and earthen or metal silos under the shelter against rain and protected from rodents (FAO 2018). Open storage gives best results only seeds are stored in a cool and dry place. Seeds of cereals and trees can be stored for long periods in such conditions without any significant reduction in seed longevity.

21.5.2 Conditioned Storage

In conditioned storage, seed viability can be maintained for many years by controlling RH and temperature of the storage environment. Continuous maintenance of such controlled conditions may be uneconomical for most crop seeds but considering the value of germplasm and high value seed stock, that cost could be justified. In tropical regions, seed viability from harvesting to planting can only be maintained through conditioned storage (Harrington 1973). Factors that should be considered while making choice of seed storage structure are

- Initial seed quality.
- Type of seed to be stored.
- Length of storage period.
- Reduction of seed weight during storage.
- Prerequisites of conditioned storage.

21.5.3 Storage in Controlled or Modified Atmosphere

Controlled atmosphere or modified atmosphere storage is a type of storage in which seeds are stored in an environment having considerably different concentration of CO_2 and O_2 as compared to normal air. Modified atmosphere needs continuous observation and manipulation of CO_2 and O_2 concentrations inside the hermetic containers or storage structure. The main goal of controlled atmosphere storage is to preserve grain and seed by controlling insects and fungal growth (Fleurat-Lessard et al. 1994) and to preserve seed quality under anoxic conditions (Groot et al. 2015). The concentration of gases inside the store varies continuously by the respiration of seeds and leakage of gases through the open spaces of doors and walls of storage structure. Therefore, it is necessary to regularly monitor gas concentration and it should be adjusted to predetermined levels by fresh air, nitrogen gas or any other chemical that can remove CO_2.

Within storage, the respiration of living organisms including (seed, insects and fungi) reduced the concentration of oxygen from 21% (normal air concentration) to 1–2% and increased the CO_2 concentration from 0.035% to nearly 2% (Chakraverty et al. 2003). Modified atmosphere can be created using combustible gases (propane and butane) to produce low oxygen and high CO_2 concentration at 13–15%. Ozone can also be used as an alternative to create modified atmosphere for storage (McDonough et al. 2010). Use of nitrogen gas and high pressure CO_2 treatment has also been reported for modifying storage environment (Navarro et al. 2012).

21.5.4 Hermetic Storage

Hermetic storage is a seed storage technique in which oxygen is reduced and replaced by increasing CO_2 that helps control stored grain insect pest without using any fumigant (Villers et al. 2008; Guenha et al. 2014; Walsh et al. 2014; Afzal et al. 2017). Hermetic storage can be used to store products without using any fumigation chemical or refrigeration practice with high quality. Plastic containers designed especially for hermetic storage can be used to store cereals and other food items. Hermetic storage is based on the principle of generation of interstitial atmosphere of sufficiently low oxygen and elevated CO_2, caused by the respiration of living organisms in the ecological system of a sealed storage (Jonfia-Essien et al. 2010). Hermetic storage technique has been used worldwide for the storage of cereal seeds including wheat, rice, barley and corn.

Packaging seeds in hermetically sealed containers or moisture-resistant bags during storage and marketing periods has been tested. The basic objective of this exercise is to keep the seeds dry and maintain a specific level that is safe for long-term storage. Traditional cloth or paper bags are least effective in maintaining seed viability, while different polyethylene and laminated bags are moderately effective. The effectiveness of a packaging material is related to its capacity to resist moisture. For hermetic storage, seeds should have 2–3% less moisture as compared to the moisture levels when they are stored in normal containers which are not completely airtight. Seed storage in hermetic bags at higher moisture contents is equally damaging as storage in traditional porous bag cause seed viability losses and aflatoxin contamination due to high seed moisture contents (Bakhtavar et al. 2019b). Complete control over humidity in seed storeroom needs a large investment for creation of such environment using dehumidifying equipment. Not everyone has such special storage facilities, so there is a need to find an alternative to this method. RH can be maintained in closed containers of small size by using desiccants that can maintain values of equilibrium moisture contents according to our own desire. Saturated salt solutions or solution of acids can be used to develop equilibrium moisture contents (Greenspan 1977). A small fan can be mounted inside the container to distribute relative humidity evenly inside the container. Silica gel is a very common desiccant and can be placed in the container along with seeds. Silica gel is coated with cobalt chloride that serves as an indicator of humidity and turns from blue to pink at RH higher than 45%. Along with this, small balls of aluminium silicate ceramics material are being marketed as seed 'Drying Beads®' and have been used to store tomato seeds (Nassari et al. 2014). Drying beads are produced from zeolite clay having microcrystalline pore structure that can tightly hold the water (Van Asbrouck and Taridno 2009; Hay et al. 2012). Rice seeds can be dried using drying beads for small scale gene bank storage (Hay and Timple 2013).

Hermetic PICS bags (Purdue Improved Cowpea Storage) are tipple layer hermetic storage bags that have been used successfully for storage of maize seed with high quality and free from insects and fungal growth (Afzal et al. 2017). The Cocoon™ of Grin Pro is also used as large scale portable hermetic storage system for rice, coca, corn, coffee sorghum, groundnut, beans, and spices in different countries (Rickman and Aquino 2004; Villers 2006; Villers et al. 2008; Jonfia-Essien et al. 2010). The GrainProSuperGrainbag II ZTM is a portable, Ultra Hermetic™ (gastight), water resistant storage option for a wide range of dry food and agricultural produce. Super bags have all the characteristics of hermetic storage system (Donahaye et al. 2001). For storage of rice seeds, hermetically sealed Super Bags have been found very effective in tropical climate by checking humid air movement. Storage in Super bags is a very successful method of seed storage to preserve quality of crop seeds (Bakhtavar et al. 2019a). Maize seed storage in hermetic Super Bag at 8–10% seed moisture contents prevents storage losses and deterioration of seed quality with respect to loss of germination, food reserves and aflatoxin contamination (Bakhtavar et al. 2019b).

21.5.5 Cryogenic Storage

Routine operation and mechanical breakdown of conditioned storage facilities is a costly practice and can be avoided by adopting cryogenic storage technique. In this type of storage, seeds are stored in liquid nitrogen at −196 °C. The main benefit of this strategy is that seeds are stored at such low temperature where there are negligible deteriorative physiological activities are occurring in the seeds (Copeland and McDonald 2001). Practically, the cost of liquid nitrogen is much less as compared to the establishment and maintenance cost of conditioned storage. One drawback of cryogenic storage is that it cannot be implemented for large scale commercial storage of crop seeds but can be successfully utilized for storage of germplasm in the seed bank. Storage of lettuce seeds in liquid nitrogen maintained the seed viability for a longer period (Walters et al. 2004). Cryopreservation can be successfully used for the conservation of medicinal legumes without any harmful effect on germination (Kholina and Voronkova 2012).

Most agronomic and cereal crop seeds can be successfully stored in liquid nitrogen, but not all seeds can bear liquid nitrogen possibly due to freezable water inside the seeds at higher moisture contents that will damage the seeds. Sesame seeds can tolerate liquid nitrogen freezing below 12% seed moisture content; above this limit, their viability decreases substantially (Copeland and McDonald 2001).

21.5.6 Cold Storage

Temperature controls the rate of enzymatic and metabolic reactions occurring within the seeds, and high temperature enhances the rate of these deteriorative reactions. According to Harrington (Harrington 1972), each 5 °C reduction in storage temperature can double the life span of the seed. This basic rule of thumb is the base of cold storage. In most cold storage, high RH is present if not properly controlled, and seeds equilibrate themselves with that high RH and its moisture content increases. So, there should be proper arrangement for humidity control, or seeds should be placed in hermetic containers to control humidity. Facilities of cold storage vary with seed volume and proposed storage period.

Seed storage at low temperature has been reported to retain maximum viability (Pradhan and Badola 2012; Liu et al. 2011). Storage temperature of recalcitrant species must be no lower than −3 °C. It is usually convenient to store recalcitrant seeds in the same facility used for stratification and seedling storage.

21.6 Conclusions

Seed longevity is a complex trait determined by a succession of events through storage that are influenced by environmental conditions. The process of seed deterioration due to free radicle attack on cell membranes and mtDNA can be delayed by controlling storage conditions such as RH and temperature that ultimately affects seed moisture contents. Seed moisture content is a critical factor in maintaining high quality throughout the supply chain. Hermetic sealed storage at low moisture contents extends seed quality and storage life through protection and repair from oxidative damage. Consequently, quality seed is critical for farmer prosperity and food security.

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