Seed Storage and Packaging

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Abstract

Storage is an essential component of seed programmes, which primarily aims at maintaining the high-quality standards of the seed from harvest till the time of sowing the crop in the next or successive seasons. In addition to this, seeds are also stored for longer durations to maintain stocks for seed trade at national and international levels as per market demands and as a buffer against crop failures in times of natural calamities or other exigencies, to maintain seeds of the parental lines for hybrid seed production in one or more seasons, to conserve active genetic stocks for breeding purposes, and to maintain germplasm for long term use. Seeds of most of the agriculturally important species are categorised as orthodox or desiccation-tolerant. Their longevity increases with decrease in storage temperature and the relative humidity of the storage environment (or seed moisture content). However, notwithstanding the constitutional differences among plant species concerning seed longevity, being a living entity, every seed undergoes deteriorative changes during storage, even in dry stores, primarily in terms of germination and vigour due to physiological deterioration, and changes brought by the presence of the pests and pathogens. A good seed programme aims at maintaining the high planting value of the seed in terms of purity, germination, vigour, and seed health during storage by taking care in seed handling, controlling the temperature and relative humidity of the store (or seed moisture in case of hermetically sealed containers), and following good sanitation

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practices. Considering that the facilities for conditioned storage may not be accessible and affordable in many situations, alternative solutions may be considered, especially for on-farm seed storage.

Keywords

Safe storage · Hermetic sealed · Moisture pervious · Safe moisture · Dry chain · Storability factors · Storage diseases and pests

1 Introduction

During seed development, germination and vigour reach their peak at 'physiological maturity'. As the seed moisture is very high at this stage, seed crop is allowed to get sufficiently dried before the seed can be harvested till a stage, commonly referred to as 'field maturity' or 'harvest maturity', when the seed moisture reaches a safe level (<15–20% in different species), but not too dry to cause shattering (Verdier et al. 2020). However, in dry season, seed moisture at harvest might go as low as 5–6%, as seen for a number of winter crops (*rabi* season) in the north western states of India. In case of wet season crops, on the other hand, harvested seed often need to be subjected to further drying before processing. Seeds of most of the agricultural and horticultural crops show a typically orthodox behaviour, where seed longevity increases with the reduction in seed moisture, and can be stored at low temperatures for prolonged storability. However, seed being a live entity, the status of viability and vigour achieved at the time of physiological maturity starts declining gradually, though very slowly initially, even on the mother plant, through harvesting and subsequent storage till the seed becomes non-viable (For more details on this please see chapter 'Seed Longevity and Deterioration') losing the ability to germinate and produce a healthy seedling (Ellis 2019). Therefore, the aim of packaging and storage is to maintain desired levels of seed quality, especially in terms of germination, vigour, and seed health, till its intended use. Though in the sequence of a seed programme, packaging is done before the final storage of seed, in order to establish the primary importance of storage, which also determines the type of packaging to be adopted in different situations, the storage requirements are discussed first.

2 Purpose of Seed Storage

Since the beginning of agriculture as an organised activity, farmers laid importance on the safe storage of seeds to plant the next crop. Seeds from the most healthy plants in a crop were harvested separately, cleaned, dried well, and saved in a cool and dry place for sowing the crop next season. With the advancement of agriculture as a specialised science, seed technology has also advanced significantly. Whether farm-saved or stored by the organised seed producers, the primary purpose of storage, accounting for more than 75% of the total produce (personal assessment based on the

Indian seed system), is to make available seed having good germination and vigour for the next planting season in the cycle of cultivation. In addition, some proportion of the total seed stock, especially of the food security crops, is maintained as a buffer stock by the government agencies or by commercial producers to fulfil the seed demand in the event of any calamity, whereas those involved in national and international seed trades also maintain some stocks for later use as per anticipated demands in other regions.

Besides these, seeds of the parental lines of the hybrids are retained mainly by the seed producers in medium-term storage for two seasons or more to save on the cost of production. Small quantities of germplasm seeds and breeding lines are preserved in long-term storage.

Suitable, cost-efficient storage management needs to be planned to meet these purposes.

3 Factors Affecting Seed Storability

Factors affecting the storability of seeds can be broadly divided into two major groups.

3.1 Seed Factors

These refer to all such internal factors which affect the physiological status of seed at the time of harvest and subsequently. These include:

- The genetic makeup of the seed.
- Growing conditions of the seed crop, any biotic or abiotic stress or nutrient deficiencies, especially during seed maturation.
- Initial seed quality, including maturity at harvest, seed size, and physical damage.
- Seed moisture content during processing and storage.
- Pathogen load and internal insect infestation and weed seeds.

3.2 Storage Factors

These are essentially the external factors that significantly influence the storage life of the seed of a species.

- Relative humidity (seed moisture).
- Temperature.
- Gaseous atmosphere.
- Packaging material.
- Structure and sanitation of the seed stores.

Besides the wide genetic variability, seed factors influencing storability need to be monitored during the raising of the mother crops. Care is taken to ensure that the seed crop is grown in an agro-climatically suitable region, with moderate temperatures and dry weather during seed maturation; the soil not be deficient in any vital micro or macronutrients; not affected by any biotic or abiotic stress during crop growth in general and seed maturation in particular; the seed crop is kept free from seed-transmitted diseases and pests; and harvested at the right stage of maturity (For more details on these please see chapters 'Seed Development and Maturation', 'Seed Storage and Packaging', and 'Emerging Trends and Promising Technologies'). Abiotic stress caused by high temperature and soil moisture and biotic stress caused by Phomopsis during seed-fill and pre-harvest stages lead to hard seeds, low seed viability, and vigour in soybean (TeKrony et al. 1980; TeKrony et al. 1996). Physiological deterioration of seed during storage is an inevitable and irreversible process, bringing down individual seeds' ability to germinate, thus lowering the germination per cent of a seed lot (For more details on these please see chapter 'Emerging Trends and Promising Technologies'). In addition, damage caused by pests and pathogens also brings down the planting value of the seed. Once the germination of a seed lot falls below the prescribed standards for a given crop species or is heavily insect-infested, such seed lots are not acceptable. If such seeds were fungicide-treated, those could not even be used for food and feed and are discarded as waste. Thus, loss of germination and damage due to pests and pathogen causes a significant loss of resources. McDonald and Nelson (1986) estimated about >25% loss of seed inventory annually due to a fall in seed quality due to poor storage which could be even more in the tropical and sub-tropical regions (Champ 1985). Since the process of deterioration can neither be halted nor bypassed entirely, efforts are directed to slow down the speed of deterioration by adopting the best storage and packaging practices as required, fulfilling the purpose of storage.

4 Management of Storage Factors

Of all the factors mentioned above, relative humidity (RH), temperature, and gaseous composition of the storage environment are the three most crucial ones that influence seed storability through direct and indirect effects and interactions between the biotic and abiotic factors. Under ultra-dry (0.3–3.0%) and low temperature (−5.0–5.0 °C) conditions, orthodox seeds retained their germinability for prolonged periods (Pérez-García et al. 2007), and such conditions are generally recommended for long-term storage of small quantities of seed, as in the gene banks. The gaseous composition of the storage space also influences seed storage, especially under hermetic conditions (Groot et al. 2015). Dry seeds usually have water potentials between −350 and −50 MPa. Being highly hygroscopic, seeds absorb moisture from the humid atmosphere till a state of equilibrium is attained. However, the chemical constitution of seeds influences the moisture absorption pattern in a given atmosphere. Thomson (1979) found that the moisture content (MC) of most cereal seeds and pulses reached safe moisture contents of 11–13% at 50–60% RH. In contrast, the oilseeds attained <10% moisture even at 70%. Malek et al. (2020) observed that the moisture content at equilibrium RH (ERH) varied in canola seeds at different temperatures and relative humidity. At all temperatures, there was a difference between water desorption and absorption curves, desorption curves being higher than the absorption curves. Therefore, in unconditioned stores, the RH keeps fluctuating; hence, the seed experiences both absorption and desorption of moisture vapour before reaching an ERH. All these factors need to be considered while planning seed storage.

A series of pioneering work conducted by EH Roberts and his team at the University of Reading, UK, on seeds of different crop species stored at varying ranges of MC/RH and temperature led to the development of viability equations to predict the germination of seeds of a given species at a given set of temperature and moisture/humidity (Roberts 1973; Ellis et al. 1989). The basic equations were further modified to better predict specific species' storage behaviour. However, there are considerable reservations about the validity of these equations, which uses universal temperature constants over the range of −13 °C to 90 °C, and moisture constants which are species-specific (Pritchard and Dickie 2003) but do not take into account critical factors such as the genotypic variations within a species, phase transition of the cytoplasm to the glassy state at MC of 5% and below, and gaseous compositions in sealed storage. Nonetheless, it does provide broad indicators for the storability of seeds of different species and emphasises the influence of temperature and humidity (seed moisture) in seed storage.

Though both the factors are essential and interact in influencing seed longevity, moisture plays a more significant role, and its management can be more energy-efficient than cooling, particularly in warm environments. High humidity is considered a bigger problem than temperature for storing any kind of seed or grains (Omobowale et al. 2016). Hence, it is important that even small reductions in ERH can equal the effect of reduced temperature without the infrastructural investment or energy input required for refrigerated storage (Dadlani et al. 2016; Pérez-García et al. 2007).

Bradford et al. (2018) suggested a relationship between the survival and growth of various microflora and insect pests on seeds with decreasing moisture content and summarised that though active respiration of seeds stops below about 95% ERH (equilibrium relative humidity refers to the MC attained by a seed lot equilibrated at a given RH), the bacteria can grow up to about 90% ERH. In contrast, at ERH below 65%, fungi cannot remain active, though storage insects are active up to below 65% ERH due to their ability to limit water loss and generate water from their food through metabolic pathways. However, they are unable to survive at ERH values less than 35% (Roberts, 1972). However, achieving ERH values <35% is often difficult, especially for seeds of grain crops with large volumes in humid environments. Seeds of some species, particularly legumes, are often prone to damage due to excessive drying, hence need care at drying. Therefore, appropriate and cost-effective drying methods must be adopted before storing seeds. Upon drying, seeds need to be stored in a sealed or dry environment to maintain germination and vigour and protect against insects. Very low ERH levels or low seed MC usually are adopted only for storage of seeds such as onion (*Allium cepa L.*), which are known to be poor storers. Rao et al. (2006) found that storage of onion seeds for 18 months or more could be achieved upon desiccation of seeds to 6 ± 1% seed moisture, sealed in moisture impervious containers, and stored at ambient temperatures or 25 °C. Low moisture storage is suitable for medium- to long-term storage of important plant species with short storage life (Ellis and Hong 2007; Hong et al. 2005).

Harrington (1972) emphasised the effect of seed moisture (and RH) and temperature and suggested two thumb rules that with every 1% reduction of seed moisture and with every 5 °C decrease in temperature, the storage life of seed doubles and the effect of these two factors are independent of each other. He further stated (Harrington 1973) that for safe seed storage of most crop species for 1–3 years, the sum of the RH and temperature at °F should not exceed 100. However, seeds can safely be stored at conditions even when the sum of the RH and temperature (in °F) is 120, provided the temperature does not contribute more than half (Justice and Bass 1978). To varying levels, management of storage factors can be achieved by natural or artificial means.

4.1 Management of Moisture

This can be achieved by (a) drying—bringing down the seed moisture to a desirable low level first, and then storing in a hermetically sealed and moisture impervious container or (b) storing seed in equilibrium with a dry environment maintained at a low equilibrium relative humidity (ERH), where it maintains a desirable moisture content. Scientific studies have established that with the reduction of equilibrium relative humidity (ERH), the storability of food products improves as the metabolic activity of spoilage bacteria, fungi, and insects slow down upon desiccation (Crowe et al. 1992). However, seeds (or grains) with higher oil content will have lower MC at a given ERH than those with lower oil content. This is because water is excluded from the hydrophobic oil bodies in the cells, reducing the water content relative to the total product weight. The same applies to seeds. The relationship between MC and ERH at a given temperature (termed an 'isotherm') is consistent for the seeds of a given species. Though the seed moisture content in a given environment is directly proportional to its ERH and reflective of the water activity of the product (Chen 2001), in case of the storage biology of seeds, use of ERH rather than MC is preferred because the effect of ERH on spoilage organisms is consistent across products regardless of their composition (Bradford et al. 2018). In the case of farm-saved seed, natural sun and wind are used (for sun or shade drying) to reduce seed moisture, and the seed thus dried is stored in suitable containers in the coolest and driest available spot. With some plant-protective measures, it was found that it may be safe to keep seeds of most grain crops for at least one crop season under uncontrolled conditions if the maximum ambient RH and temperature do not exceed 70% and 30 °C, respectively, for more than three months in a year (Agrawal 1982). For maintaining germination in commercial seed lots, care is needed for safe drying and equilibrating at a safe RH.

4.1.1 Seed Drying

Drying is the process of removal of moisture from the seed. The extent of drying operation is determined by the initial seed moisture content and the level to be achieved, which in turn will be determined by the following factors:

- Type of seed: This will consider seed structure, composition, and longevity behaviour (whether the species is a poor, moderate, or good storer).
- The abundance of natural sunshine and wind at the location and availability of infrastructure and machinery to use artificial drying economically.
- Conditions of storage to be followed: It is crucial to know if the seed will be (a) packed in vapour permeable containers and stored under ambient conditions; (b) packed in vapour permeable containers and stored in RH and temperature conditioned stores; (c) packed in hermetically sealed containers and stored under ambient conditions; or (d) packed in hermetically sealed containers and stored in conditioned stores.
- Value and volume of operations: The quantity of seed to be dried and the value of the seed per unit weight are the other important considerations in commercial seed operations.

4.1.2 Natural Drying

Several studies have shown that seeds of field crops and vegetables equilibrated at 60–70% RH attain equilibrium moisture content (EMC) of ~ or <12%, which is considered safe for post-harvest handling (Harrington 1960; Leopold and McDonald 2001). Hence, seed crops harvested in favourably dry climates seldom need much drying before threshing and conditioning either for on-farm or commercial storage. When the MC of the harvested seed is high, it may need to be pre-dried before threshing and further dried before storage.

Open-air sun-drying is an effective and practical method of bringing seed moisture to a safe level. Care is needed to ensure that the seed is laid in middle layers and turned periodically for uniform drying. As high temperatures can be detrimental to seeds having high MC (Brooker et al. 1992), the temperatures at drying should preferably be kept < or not above 40 °C. Starchy seeds generally withstand higher drying temperatures than oil-rich seeds (Thomson 1979).

In the subtropical and tropical regions with ambient temperatures of 40^0 C and above, shade-drying with assisted aeration (using domestic-purpose pedestal fans) is often preferred. It also protects seeds from the possible damage caused by the UV radiation of sunlight. Hanging porous seed bags or earheads upside down from the ceiling of the storage structure is also an effective method of on-farm natural seed drying.

4.1.3 Commercial Drying

Depending upon the initial seed moisture at harvest, seeds are dried using single- or two-stage drying methods before storage. Commercial seed drying is of three types (For more details on this see ‘Seed Processing for Quality Upgradation’):

1. Layer drying.
2. Batch drying.
3. Continuous flow drying.

Following the main principles of each type of drying, additional features may be added as per needs.

Layer drying (also referred to as bin layer drying) is mainly used for in-storage drying in which seed is dried in layers, and the airflow ducts are built at the bottom of the bin. Once the first layer is dried up to a certain level, a second layer is added; thus, each seed layer is partially dried before the next is added. Several layers will be added, and these will reach moisture equilibrium over a period of time. A stirring and mixing device improves moisture spread across the layers. This type of dryer is more suitable for on-farm storage of seeds.

Batch drying, suitable for both stationary and portable units, dries seeds in batches. Slightly heated air is passed through the seed layers from bottom to top. With the onset of drying, a moisture gradient is created from bottom to top, and moisture is removed from the seed till an equilibrium is reached. Further drying is possible only by raising the drying temperature or the rate of the airflow, or both. Like layer dryers, a stirring device is also used to improve drying in batch dryers. In a batch-type dryer, a fixed amount of seed can be dried at a time.

Besides forced air, both layer and batch driers may have supplemental heating, but since the seed is not moving, it requires a cooling period after drying once the heating is turned off.

In *continuous flow dryers*, unlike layer and batch dryers, the seed moves continuously from the inlet to the outlet through the drying and cooling chambers. The heated air is forced through the seed column from a heated air plenum. This method is suitable for drying a large quantity of seeds. The drying efficiency is highest in continuous flow type dryers, followed by the batch type (better in two-pass type than the single pass) and layer type dryers, respectively.

For better drying efficiency, seed dryers have the option of fitting a dehumidifier to dry the air before it is heated and passed through the seeds. The air dryer lowers the relative humidity of the air by decreasing the total moisture in the air. As a result of dehydration, the temperature is raised; thus, the need for heat to be provided by the heaters is lowered, reducing the fuel cost (Justice and Bass 1978).

In commercial seed production units in warmer and humid regions, dealing with large quantities of field crops during peak seasons, two-stage drying may also be adopted. In this, harvested seed with high MC (~20%) is first dried to a moderate level (~15 to <18%) and stored. Once all seed lots or the whole quantity of seed is dried to such a moisture level, which is safe for short storage, the seed lot is dried to the moisture level recommended for safe storage (Khare and Bhale 2014).

In addition to the above-mentioned basic dryer designs, there are dryers for special purposes, e.g. rotary dryers, used for dying small batches of vegetable seeds; ear-corn dryers for drying seed-in-the-cob of maize; box dryers for drying limited quantities of pre-basic/breeder or basic/foundation seed. Fluidised bed seed dryers can also be used for small-seeded species.

4.1.4 Management of Temperature

The independent yet interactive influence of temperature and humidity on seed longevity is well documented, recognised, and reflected in early prepositions of Harrington's thumb rules, as well as Robert's viability equations. However, in later studies, it has become evident that the humidity of the storage environment plays a bigger role in seed longevity than the temperature. When seeds are dried to a reasonably low MC, their storability gets significantly enhanced, compared to the longevity behaviour of seeds held at higher moisture even at temperatures above 25 °C. Contrarily, high moisture seeds can only be stored at temperatures below 10 °C, but not at sub-freezing temperatures. At temperatures above 25 °C, seeds with moisture above 12–14% experience higher physiological and pathological deterioration, whereas at subfreezing temperatures, seeds with high MC may experience freezing injury. Comparing the storability of the primed seed of rice (dried to 10.5% moisture, under different conditions of temperature, RH, and availability of air), Wang et al. (2018) observed that the viability of primed rice seeds did not reduce when stored under low temperature (LT <5 °C)—vacuum (V); room temperature (RT ~30 °C) and vacuum (RT-V), or room temperature, aerated and low humidity (LH 20–26%) conditions (RT-A-LH), but was significantly reduced at room temperature-aerated-high humidity (60% and more) conditions (RT-A-HH). Hence, the detrimental impact of storage temperature was evident when the seeds were stored under high RH and aerated conditions. In a vacuum, the increase in temperature (30 °C) did not reduce the longevity of primed seeds in a short storage study, indicating the vital role of air (or its absence) in determining seeds' storability.

4.1.5 Gaseous Composition of the Storage Environment

It is well known that seeds dried to low MC (<5%) and stored in hermetically sealed containers (laminated and poly-lined/polythene, metal cans, glass, etc.) can store well for more extended periods at ambient, lower or higher temperatures as compared to those packed in non-sealed containers (Grabe and Isley 1969). The impact of gaseous components in the storage environment on seed longevity has been studied extensively in seeds maintained in hermetically sealed containers (Bockholt et al. 1969; Lougheed et al. 1976; Justice and Bass 1978; Bennici et al. 1984). Storing seeds in a vacuum, CO_2, or other inert gases has been tested for extending longevity, and variable results were reported. Groot et al. (2015) observed that the ageing of dry seeds was accelerated by the presence of oxygen in the environment and suggested storing seeds in anoxia for prolonged germplasm storage.

4.2 Seed Packaging

After the seed is dried to an optimum moisture level, it needs to be packed in such containers that the moisture content does not exceed the safe level for the kind of storage. Seed moisture below 12% is considered safe for storing most seeds of field crops in moisture vapour permeable bags for at least one season under ambient conditions. For vapour, impermeable containers seed moisture in the range of 6–8%

is considered safe (Anonymous 2013). Seeds in bulk are commonly packed in gunny sacks/burlap/cotton/multiwall paper/high-density polyethylene (HDPE) bags or moisture-resistant bags and cocoons, whereas seeds in smaller quantities can be stored either in flexible or rigid materials as per needs.

Packaging materials are characterised by the degree to which they can resist the passage of gases and vapour. In different types of flexible packaging materials, the gases and moisture vapour can permeate (a) through the macroscopic pores and canals (e.g. kraft paper and parchment paper); (b) by the process of diffusion of the gas through the main bulk, and evaporation from the outer surface (e.g. uncoated cellulose, polyethylene, and cellulose acetate); and (c) through the pinholes on the surface of the packaging material, as in case of aluminium foils (Ranganna 1986).

Introduction of ultra-hermetic flexible UV-resistant cocoon made of polyvinyl chloride (GrainPro®), which have low permeability to air and moisture prevents the exchange of air and moisture into the bag and reduces insect activity considerably. Though more suitable for grain storage, these have shown promising potential for chemical-free, safe seed storage without cooling if the initial seed moisture is brought down to a safe level ($<10\%$). Developed by the International Rice Research Institute (IRRI) and manufactured by GrainPro Inc., Super Grain bags maintained germination for 9 to 12 months under natural conditions (Asian Scientist, 30 July 2012; https://www.asianscientist.com/2012/07/tech/irri-grainpro-supergrainbag-2012). These bags come in 25 or 50 kg capacity and also have ports for fumigation of seeds or drawing seed material.

Moisture-proof packs (having low moisture vapour transmission rates) made of films of polyvinyl, polyethylene, cellophane, polyester, aluminium foil, etc. are generally used for smaller and sealed packaging. Some of these, e.g. polyester, also have low permeability rates to CO_2 and O_2. These are also suitable for vacuum sealing or filling with neutral gases to slow down the process of ageing. A combination of two or more different layers can be fused for better tensile strength and resistance against moisture vapour and other gases, e.g. CO_2 and O_2. However, while packing seeds in moisture-proof containers, caution is needed to check the seed moisture content. The Indian Minimum Seed Certification Standards (Anonymous 2013) provide specific requirements for keeping seed MC in moisture vapour-proof sealed containers. Storing chilli seeds at ~7% MC in partial vacuum (Doijode 1993) sealed packaging in laminated paper-Al foil-polythene bags under ambient conditions was found to maintain satisfactory levels of germination for three years.

4.3 Storage Structures

The important factors determining seeds' longevity during storage are the seed moisture, type of storage container, and storage environment. These factors generally interact, leading to many physiological and biochemical changes in the stored seeds, which result in deterioration of seeds both in quality and quantity, especially in tropical and sub-tropical countries.

Seed is stored in bulk for varying periods from harvest to its use for the next sowing. When the seed crop is harvested, it is often stored in drying sheds or stacked in large heaps covered with waterproof material, e.g. tarpaulin, for short periods before threshing, conditioning, and storage. Such structures only protect against rains, birds, and mechanical damage. However, after drying and processing, the seed needs to be stored in bulk in structures preferably built with waterproof walls and roofs and sealable openings for controlled ventilation and periodic fumigation. It must not allow water entry by seepage from the ground or walls. Columns must be widely spaced to permit the easy use of forklifts and movement of bags in stores, and ceilings should be high to stack seed bags up to 5 m high. Seed stores in sub-tropical and tropical regions are built at least 1 m above the ground, and rat traps are installed at possible entry points to check rodents. Seed warehouses with metal roofs must be suitably insulated and usually painted white for maximum reflectance.

Seeds stored in bulk cause heat build-up and need to be shifted or upturned periodically to break any hot spots. Aeration inside the stores with pedestal or moving fans help in dissipating heat. In modern seed stores, multiple sensors are fixed at different points, monitoring the temperature and humidity inside the stores, which can turn on aeration and cool the seeds when required (Desai et al. 1997). It is also important to ensure that the seed material for storage is almost free from any seed-borne pathogens and pests. The seed material in bags and sacks should be stacked on wooden pallets maintaining proper distance from the walls and the ceilings.

Depending on the type of seed material and purpose, different storage structures are considered for maintaining seed quality in commercial stores.

1. Storage under ambient conditions with or without ventilation: Commercial-scale unconditioned seed storage structures rely much upon natural cooling and ventilation to minimise the adverse effects of heat build-up. In temperate climates, bulk seeds can safely be stored by controlled natural ventilation, whereas in warm, humid environments, ventilation with outside air could be counterproductive (Copeland and McDonald 2001). Seed sacks/bags/piles/single layers/open containers can be kept for a short period, such as pre-processing or before final packing and storage, or for 6–8 months from harvest till the next cropping season in moderate environments. Measures are taken specially to protect seeds from rodents and birds.
2. Storage with only the control of moisture: This kind of storage is more suitable under temperate conditions where the temperature remains relatively cool throughout the year. Seed moisture is controlled either by packing pre-dried low moisture (6–8% moisture) seeds in vapour-resistant bags/containers or by packing seeds in vapour-permeable bags/sacks and using dehumidifiers. Since control of storage temperature in warmer regions, requiring uninterrupted power supply for refrigeration often poses a big challenge, the use of in-the-bag desiccants and frequent use of dehumidifiers, especially during the wet season, to maintain the RH of storage environment $<70\%$ maintains seed quality during

storage at least for one season, and also to carry over the unsold stocks for the next season.

3. Storage in low-temperature conditions: Low-temperature storage modules are often maintained by seed companies in warmer regions, dealing with seeds of a variety of crops. High value, low volume seeds of vegetables and flowers, having poor storability are dried to a reasonably low MC, packed in hermetically sealed moisture vapour impervious containers, and stored in low-temperature storage units (modules). However, care should be taken for seeds in pervious moisture containers stored under low-temperature conditions. RH of the ambient air increases with lowering the temperatures raising the seed MC. Thus, when brought to higher temperatures, seeds exiting such storage will be more susceptible to rapid deterioration.
4. Storage under controlled conditions of RH and temperature: This type of storage is used for storing seeds in bulk for at least two or three years and is cost-effective only in the case of high-value seeds, e.g. hybrids; inbred parental lines of the hybrids, especially in case of double or three-way crosses (e.g., maize); or very poor storers, e.g. onion. This is also commonly used for most vegetables (especially the hybrids or small-seeded ones) and flower seeds, owing to their high value per unit weight and smaller bulk. The temperature and RH are typically maintained at 20 °C and 50% (Copeland and McDonald 2001). The operation of this type of store requires an uninterrupted electricity supply.
5. Moist cold storage with control of temperature for limited period storage of desiccation-sensitive seeds from temperate regions: Seeds of recalcitrant seeds with high MC may be stored at low temperatures (just above freezing) for research purposes. The stores are maintained near saturation RH, and the seeds are moistened periodically. However, seeds are seldom stored in this way for commercial use.

4.4 On-Farm Safe Seed Storage

For on-farm seed storage, which accounts for >50% of seed used in subtropical/tropical regions, seeds are sun-dried, air-cooled, and then stored in cool and dry conditions in clean storage containers or structures. The containers of various kinds can be used for the purpose, ranging from jute/hessian bags, HDPE (interwoven) bags, cloth bags, clay pots, metal bins, mud-plastered bamboo baskets, etc. Mud-plastered structures are also used for larger quantities of grains and seeds. Many plant parts having insect repelling properties can be used in these containers/structures (Francis et al. 2015). However, for safe storage in a humid climate, it is not always enough to only dry the seed, unless it is also packed in an atmosphere that will not allow entry of moisture vapour (as in moisture vapour impervious containers). At times, it is difficult to dry the seed below 12% MC, especially for the rainy season crop, which is harvested when the ambient RH is still fairly high (~70%). For storing seeds of high-volume cereal crops, held at 13–14% MC, moisture vapour impermeable bags or bags made of sheets impermeable to gaseous exchange are useful. Storage systems such as Grain Pro™ Superbags or hermetic cocoons (De Bruin et al. 2012; Murdock et al. 2012; Rickman and Aquino 2007) are both moisture-proof and impervious to oxygen, which do not allow the insects to survive (www.grainpro.com) and can be used for one to two season storage. These bags and larger-scale cocoons can significantly improve commodity storage when properly utilised (Afzal et al. 2017).

Another cost-effective way, very promising for on-farm conservation of seed, is the use of zeolite beads, also known as 'drying beads' inside seed bags or drums to dry seeds safely at ambient temperatures maintaining seed viability and also protecting against storage insect pests (Bradford and Asbrouck 2011; Kunusoth et al. 2012; Sultana et al. 2021). As the zeolite beads can be regenerated thousands of times by heating, they can be used repeatedly. Bradford et al. (2018) proposed the dry chain concept to store food products, grains, and seeds safely. Analogous to the cold chain, in which products are maintained at low temperatures throughout storage and distribution, as in the case of fresh foods, in the dry chain, products are dried to low MC and stored in water-impermeable packaging. The dry chain using drying beads and containers resistant to gaseous exchange offers safe storage of seeds for the short to medium term, at relatively low energy consumption and cost, as refrigeration is not required. This approach can be practised effectively for on-farm seed storage by the farmers or for maintaining moderate amounts of seeds in the community seed banks, especially in humid locations (Dadlani et al. 2016). On the other hand, in-silos drying and storing are common with farmers with large holdings.

5 Management of Diseases and Insect Pests During Storage

While the problems of rodents and birds are mainly managed with modification in storage structures and mechanical devices, fungi and insect pests can be controlled by managing seed moisture, relative humidity of the storage environment, and treatment with needed pesticides (fungicides and insecticides). This is also known as integrated pest management.

5.1 Seed Health Management During Storage

Seed health is an important criterion of seed quality, which mainly refers to the presence or absence of disease-causing organisms, such as fungi, bacteria, viruses, animal pests such as nematodes and insects, or physiological disorders due to deficiency of trace elements. The problems of diseases and pests during storage are more aggravated in the warm and humid regions, making it difficult to maintain the prescribed levels of seed vigour and viability from seed harvest till the next sowing season. As the number of small farmers is high in the sub-tropical and tropical countries where farmers use about 60 to 70% of farm-saved seed for sowing, these are highly prone to damages caused by pests and pathogens. According to some rough estimates, nearly 10% of the food grain is lost in storage due to microbial spoilage and insect attack, which also include grains saved for seed purpose.

5.2 Microbial Damage

Seeds become vulnerable to various types of pathogens and saprophytes during storage, especially under humid and warm conditions. Fungi form the major group of microbes causing seed damage, which are classified as storage fungi. Nearly 150 species of fungi have been found associated with grains and seeds in storage (Dharam Vir 1974). Mechanical damage in the seeds, cracks, breaks, or scratches in pericarp or seed coat developed during threshing and processing substantially facilitate invasion of fungi, which find their way to the storage go downs.

The storage fungi can grow without free water, at ERH of 70–90%. Some common storage fungi infecting seed include *Aspergillus*, *Penicillium*, *Rhizopus*, *Fusarium*, *Cladosporium*, *Alternaria*, *Mucor*, *Chaetomium*, *Epicoccum*, etc. As most fungi spp. primarily invade the embryo, the infected seed may appear normal during the early stages of infection. However, in later stages, discolouration and distortions of seeds including reduction in seed size, shrivelling, and seed rots are some of the common manifestations of seed-borne pathogens, besides causing seedling decays, pre- and post-emergence mortality, and seedling abnormalities. As the pathogens are well-established, embryos become ungerminable, and the seeds appear discoloured, reducing the seed quality, as well as making the grains unfit for human and animal consumption. Thus seed-borne fungi decrease the market value, germinability, and nutrition of the produce. Excessive fungal growth may also result in heating, caking, and decay. Besides losing viability and vigour, this brings about biochemical changes leading to the production of toxins and reduction in seed weight.

Studies have shown that the invasion of fungi leads to both physical and chemical changes in the seeds. Misra and Dharam Vir (1992) observed an increase in milling losses ranging from 34.0 to 58.6% in discoloured rice grains. Prasad et al. (1990) observed changes in fatty acids, glycerols, sugars, and amino acids in radish seeds infected with *A. flavus*. Similarly, Dube et al. (1988) observed changes in starch, fatty acids, and sugars in wheat grains infected with *A. flavus* and *A. niger*. Joshi et al. (1988) reported a 73% reduction in starch content and an increase in the amount of reducing sugars and phenolic contents in pearl millet seeds infected with storage fungi. Aflatoxins were reported by Bilgrami and Sinha (1983) in infected seeds of maize, groundnut, and other agriculturally important crops used as foods and feeds. Vaidehi (1997) showed that the biochemical changes brought by storage fungi lowered the quality of maize grains. These fungi may be present as dormant spores or mycelium on the seed surface or below the pericarp, which activate and multiply at a fast rate under favourable growing conditions of storage.

Though initially the incidence of field fungi is higher in seeds and that of the storage fungal flora associated with different seeds are initially low, it increases with an increase in the storage duration, whereas the field fungi reduce with the advancing

Table 1 Influence of seed mycoflora on soybean seed germination during ambient storage (Gupta and Aneja 2004)

Storage period (months after seed treatment)	Seed germination[a] (%)	Seed mycoflora[a] (%)	Seed moisture[a] (%)
0	92.0	1.05	7.8
2	86.5	2.4	5.9
4	92.8	3.4	6.6
6	85.3	2.7	9.9
8	50.8	5.9	8.6
10	44.3	4.6	8.9
12	38.3	5.0	8.8
Correlation coefficient (r)	−0.872		0.35

[a] Average of 20 treatments

storage. Proliferation of storage fungi leads to several pathogenic and biochemical changes, resulting in the decrease of seed viability. A significant negative correlation ($r = -0.793$) has been observed between seed viability and the load of mycoflora with the advancement of storage (Table 1).

5.3 Storage Insect Pests

More than half a dozen insects are commonly found associated with stored seed/grain in tropical and sub-tropical environments. These can be grouped into two major categories as internal and external feeders.

Primary or internal feeders: These insects mostly lay eggs inside or on the seed and complete almost entire larval and pupal life inside the seed, only to emerge as adults. They cause significant damage to the seed, which is not visible from the outside. It leads to loss of germination and vigour. The most common of these are:

Rice weevil, ***Sitophilus oryzae*** **(Coleoptera: Curculionidae)**.
Lesser grain beetle, ***Rhyzopertha dominica*** **(Coleoptera: Bostrichidae)**.
Pulse beetle, ***Callosobruchus maculatus***(**Coleoptera: Bruchidae**).
Angoumois grain moth, ***Sitotroga cerealella*** (**Lepidoptera: Gelechiidae**).

Secondary or External feeder: This group of insects feeds on embryo/germ and endosperm from outside. They may attack the whole seed and damage the embryo if the seed moisture content is higher than the recommended, or feed on the damaged/infested or mechanically broken seed. These insects in their different stages of development and growth are generally visible on the seeds. The most common of these are:

Red rust flour beetle, ***Tribolium castaneum*** **(Coleoptera: Tenebrionidae)**.
Saw-toothed beetle, ***Oryzaephilus surinamensis***(**Silvanidae: Coleoptera**).

Rice moth, ***Corcyra cephalonica*** **(Lepidoptera: Pyralidae)**.
Almond moth, ***Cadra cautella*** **(Lepidoptera: Phycitidae)**.

It also includes insects and mites that develop after the infestation of other pests as they feed on cut and broken seeds, moulds and debris, dead insects, and animal wastes such as common grain mite and cheese mite psocids.

Knowledge of the various sources of infestation is crucial for better managing insect pests in the store. These are:

- **Field**: Some insects like bruchids, *Sitophilus oryzae*, and *Sitotroga cerealella* infest seed crops at the reproductive stage in the field. They come along with the harvested produce and multiply during the pre-storage or storage. The infestation is usually detected at the time of the emergence of adults.
- **Stores/godowns**: Insects or their stage(s) hiding in the cracks and crevices, electrical fittings, spillage, filth, etc. are the primary source of the infestation in the seed stores and godowns.
- **Reused old bags/containers and seed transport system:** Adult insects as well as those in developmental stages hide in the weavings, nooks, and corners; infest the seed when stored in such contaminated bags/containers, especially when reusing old bags or in the vehicle while being transported.

Essential components of Integrated Pest Management (IPM) against storage insects are:

- **Prevention:** includes proper seed drying, scientific method of storage, management of storage insect pests, and prophylactic treatments.
- **Inspection and monitoring:** regular inspection and monitoring of insect infestation in the godown and seed lots to make timely and correct decisions on the need and type of control measures.
- **Intervention:** management of insect infestation through appropriate control measures.

5.3.1 Monitoring and Detection of Insect Infestation

Considering the rapid multiplication of insects, regular monitoring and detection of insects in seed stores are necessary for early warning and in taking appropriate and timely control measures. Detection delays may result in pest outbreaks, causing severe contamination of seed materials and quantitative loss. It also helps in achieving better effectiveness of fumigation and other pesticide treatments.

5.3.2 Monitoring of Insect Infestation in Seed Stores and Bulk Godowns

- **Visual Inspection**: It includes inspection of the stores and godowns (both before and after processing) for live, flying, or crawling insects in every season, particularly the warm and humid pre-monsoon, monsoon, and rainy months. Detection of live insects or their castings in sweeps and the presence of flour deposits on bags caused by lesser grain borers indicate insect infestation. The presence of the web in undisturbed places is also a sign of lepidopteran infestation.

- **Light traps**: Most insects are nocturnal and phototropic. Light traps detect the presence of insects and their build-up. Light traps with an electrocution net kill insects attracted to them and help control insects. Mohan et al. (1994) used a 4 W ultraviolet light (peak emission at 250 nm) set at 1.5 m above ground level in the alleyways and corners of godowns. This detected the presence of *R. dominica* accurately.
- **Sticky traps**: These help in the early detection of insects, especially when placed at the top of bins.
- **Traps for crawling insects**: It provides a hiding place and is available in various designs. It can be used with pheromone lures for specific insects or food baits to enhance the capture of multiple species.
- **Pheromone traps**: Unlike light traps, pheromone traps are baited with synthetic chemicals that influence insect behaviour. These chemicals are species-specific and help in better monitoring of particular insect pests. Traps have also effectively detected insects at low population levels early. Pheromone traps are now available with adhesive glue, to which insects get stuck, which helps in removing a proportion of the population (mass trapping).

Detection of External Infestation in Seed Lots

(a) **Direct examination:**
  - Two samples of 200 seeds each are visually examined using a magnifying glass (10X) or stereoscopic microscope with light.
  - Live and dead adult insects, larvae, grubs, etc. are separated, counted, and recorded as numbers per weight of the sample.
  - Insect-damaged seeds are separated and counted, including those whose germ (embryo) has been damaged or have an escape-hole (s) or eggs adhered to them.
  - Other seeds with no visible symptoms of insect injury are subjected to further tests to detect an internal infestation.
  - The number of internally infested seeds is added to the number of seeds found externally damaged by an insect for the final calculation of insect-damaged (ID) seeds.

- There are different methods for detection of internal infestation:
  (a) Dissection method
  (b) Translucent method
  (c) Flotation or specific gravity method
  (d) Staining method
  (e) X-ray or radiography technique
  (f) Acoustic (sound) detection system

(g) CO_2 detection method
(h) Breeding out method

6 Good Storage Practices as a Preventive Measure

It requires the maintenance of storage facilities to an adequate standard and efficient control and handling of stocks. Regular and critical inspection of stores and stocks should be done to maintain good storage hygiene. Moreover finally, the chemicals should be the last option on a cost and need basis. The application of pesticides to stored products should be kept minimum. It has two components of pre-storage and in-storage measures.

6.1 Pre-Storage Preventive Measures

6.1.1 Preparation of Seed Stocks

- The seed stock should be clean and free from broken or damaged seeds.
- Ensure drying of seed to moisture content (MC) $<10\%$ and for paddy ($\leq 13\%$) before storage.
- Pulse seeds may carry insect infestation from the field, which is detected when adult insects emerge from the seed in the pre-processing hall before processing. Therefore, pulse seed should be dried in the sun to kill all internal infestation or fumigated immediately after arrival in the godown to avoid insect multiplication.
- Ensure new harvests do not carry field infestation in other crop seeds. Fumigate if the live insect is detected.
- Mix premium-grade Malathion 5%D @200 g/t of seed or Deltamethrin (K-Othrin 2.5 SC) @ 40 mg/kg seed. Treated seed should never be used as food or feed.

6.1.2 Preparation of Seed Store/Shed

- Clean all the structures from debris, webs, and spillage. Disinfect concrete floor and walls with malathion 50 EC or fenitrothion 50 EC @ 50 ml in 5 L water/100 m^2 floor using a knapsack sprayer. Wet all surfaces and fill the crack and crevices to kill hiding insects.
- For non-commercial purposes, treat old seed bags with hot water (>50 °C) for 15 min and dry them before use or treat with malathion @ 10 mL/L water or Deltamethrin @ 02 mL/L water per 20 m^2 bag surface area or fumigate before re-use.
- Seed treatment with Spinosad (Tracer 45 SC) and Indoxacarb (Avant 14.5 SC) @ 2 ppm provide effective (ID: 0.10% and 0.13%, respectively) control of storage insects infesting rice seed up to 12 months of storage under ambient conditions, whereas in untreated lots, seed damage was 7.4% control (Padmasri et al. 2017: https://www.researchgate.net/publication/324476766).

- Treatment of wall or empty surface before storage of seed with following insecticides, if required:
  Malathion (50 EC) at 10 mL/L of water @ 5 l/100 m^2.
  Deltamethrin (K-Othrin 2.5 SC) at 40 mg/L water @ 5 L/100 m^2.
  Use of insecticides will be as per the prevailing regulations in a country.

6.1.3 Thermal Treatment

Heat treatment has been used to control the development of pathogens and insects. Both high and low temperatures are reported to be effective against most storage insects (Table 2).

6.1.4 Solar Heat (Solarization)

A solar heater is made of dark cloth or black plastic sheet, which can trap natural ambient temperature to destroy pests. It is particularly effective in sub-tropical and tropical regions where ambient temperature can exceed 40 °C during summer. A solarisation cover can elevate the temperature to >60 °C in about two hours, lethal to many storage insect pests like pulse beetles. Chauhan and Ghaffar (2002) found that pulse beetles at all stages, present in pigeon pea seeds, were killed upon solarisation in polyethylene bags at ICRISAT, Hyderabad, upon reaching the temperature up to 65 °C. Moreover, seeds, thus solarised, remained protected from insect damage even after 41 weeks of storage under ambient conditions of seed store. There was no adverse effect of solarisation on the germination of seeds. This technique is particularly useful for on-farm seed storage. On-farm testing of Sunning and Sieving (S & S), that is, removal of killed insect debris by sieving after solarisation, showed it was as effective in combination with seed treatment with insecticide 1.6% Pirimiphos methyl or 0.3% permethrin after four months of storage. Solarisation of seeds in clear polythene (700 gauge) packets for six days (3 h on each day) was found to be

Table 2 The response of stored-product insects to temperature (Fields and Muir 1996)

Stage	Temperature zone (°C)	Effects
Lethal	>62	Death in less than 1 min
	50 to 62	Death in less than 1 h
	45 to 50	Death in less than 1 day
	35 to 42	Populations die out
Sub-optimum	35	Development stops
	33 to 35	Slow development
Optimum	25 to 33	The maximum rate of development
Sub-optimum	20 to 25	Slow development
	13 to 20	Development slow or stops
Lethal	03 to 13	Death in days (un-acclimatised), and movement stops
	−10 to −5	Death in weeks to months if acclimatised
	−25 to −15	Death in minutes, insects freeze

an effective treatment for reducing insect damage at most of the National Seed Programme (NSP) centres in India (S.N. Sinha, personal communication).

6.1.5 Cold Storage

Low temperature (<20 °C) storage not only slows down physiological seed deterioration but also restricts the growth and development of storage insect pests in the godowns, thereby improving their shelf life. Most storage insects' life cycle gets prolonged, but they are not killed. The relative humidity (RH) in the enclosed space significantly affects the survival of insects under low temperatures. RH <30% is ideal for safe storage of seeds for medium-term period storage (4–5 years). Various factors such as insect species and its stage, density, and distribution in the seed lots, air temperature and relative humidity, length of the exposure period, type of seed and its moisture content, and the initial health status of seed (field infestation, if any) determine the efficacy of insect control in cold storage.

6.1.6 Controlled Conditioned Seed Storage

The hot and humid environment is ideal for insect activity. It also affects seed quality and its shelf life. Hence, low temperature (<20 °C) and low RH (<50%) environment in the seed godown improves the shelf-life and seed quality for a more extended period. Cold storage technology is expensive; therefore, it is suitable for storing low-volume, high-value (LVHV) seeds. In high volume storage of seeds of wheat, paddy, etc., such facility would be uneconomical. The cold storage facility is commonly used with the dehumidifier to store the carry-over seed stock at <20 °C and <50% RH for 1–2 years, or at 15 °C and 30% RH for storage of vegetable and nucleus seeds for 3–5 years period. The dry chain approach can also be used in place of a dehumidified atmosphere storage to control insect pests.

6.1.7 Fumigants

A fumigant is a chemical in vapour or gaseous state that when released penetrates the objects or enclosed areas in such concentrations that are lethal to targeted pest organisms. This excludes aerosols, particles suspended in the air, often called smokes, fogs, or mists. The most important and useful properties of the fumigants are that these penetrate the fumigated materials, neutralising the target organisms and diffuse afterwards.

There are many chemical fumigants recommended for the control of storage insects. A list of such fumigants and their properties are described below, though many of these are now not in use in most countries due to environmental and human health hazards. Many insects have also been reported to have become resistant to some of these. Only phosphine (PH_3) was found safe for all kinds of seeds with up to four fumigations in a multilocation NSP trial (S.N. Sinha, personal communications, ICAR-IISS, Mau) (Table 3).

Table 3 Important fumigants, their dosages, and exposure period

Fumigant	Dose mL or g/m^3 space	Dose mL or g/t seed	Exposure period (h)	Repetition (number)	Ovicidal toxicity
ED: CT mix.	480	740	24	2–3	Low
EDBr	32	56	24	02	Normal
CS_2	480	740	24	01	Low
MBr	32	56	12	02	High
PH_3	**02**	**03**	**5–7**	**3–4**	**Moderate**

6.1.8 Hydrogen Phosphide or Phosphine (PH3)

- Aluminium phosphide (AlP) tablets are available for specific use in the names of 'Celphos, Quickphos', etc. It weighs 3 and 1 g of Pellets (used against rodents) and liberates 1/3 phosphine gas of its weight.
- Ammonium carbonate, ammonium bicarbonate, urea, and paraffin are also added. The chemical reaction is.
- $AlP + 2NH_4\ OC\ (O)\ NH_2 + 3H_2O = \uparrow PH_3 + Al\ (OH)_3 + \uparrow 4NH_3 + \uparrow 2CO_2$
- CO_2 suppresses the flammability of PH_3 while diffusing from the tablet in the presence of moisture. Ammonia is a warning gas, and it reduces fire hazards.
- Aluminium phosphide produces a carbide or garlic-type odour. It is heavier than air and has low water solubility. It is highly inflammable per se, a safe and convenient method to evolve gas.
- The larvae and adults succumb more easily. In comparison, the eggs and pupae are usually the hardest to kill. The tolerance of eggs and pupae can be overcome by relatively long (10-day) exposure periods.
- Phosphine does not affect the germination of cereal seeds, and legumes with one or two fumigations at comparatively high concentrations. Up to four repeated applications showed no adverse effect on the viability and vigour of different crop seeds in a multilocation trial under the National Seed Project in India (S.N. Sinha, personal communication).

Thus, Phosphine is an effective fumigant for controlling storage insect pests which may be used if permitted by the concerned regulation.

7 Pre- and Post-Harvest Strategies for Disease Management

Storability of seed and incidence of diseases during storage are much influenced by the health status and quality of the seed at the time of harvest. Seed production, therefore, should be planned in safe areas and in appropriate seasons where the occurrence of major seed-borne diseases is known to be minimal or nil. Pre-harvest sprayings with suitable pesticides or bio-control agents and harvesting the crop at the proper maturity stage also help maintain the seed quality during storage. Exposure of the seed crop to biotic and abiotic stresses, especially during seed maturation, influences seed vigour and longevity (Siti et al. 2019).

Discolouration of seed due to pre-harvest rains and the occurrence of diseases reduces the planting and market value of grain seeds, which are mostly sold without any coating or colouring. Therefore, in regions where diseases or discolouration are expected, a pre-harvest prophylactic spray may be applied. Govindrajan and Kannaiyan (1982) observed a reduction in grain discolouration of rice through pre-harvest spraying with copper oxychloride. Seed discolouration in paddy was also reported to increase with higher doses of nitrogen and phosphorus, whereas wider spacing in the field resulted in lesser discoloration (Mishra and Dharam Vir 1991). According to Deka et al. (1996), application of Maneb at the boot leaf stage, followed by a spray with common salt, was effective in reducing the discolouration in paddy grains. However, in some crops, mainly soybean, peanut, and other legumes, the darkening of the seed coat is reported to be indicative of oxidative reactions and not associated with disease (Marzke et al. 1976; Siao et al. 1980).

The association of fungi is reported to be more in the seed crops grown and harvested in the wet season. A higher percentage of storage fungi is generally observed in samples obtained from areas with high humidity (Indira and Rao 1968). There are significant variation in the propensity of storage fungi on seeds of different species and varieties, due to their chemical constituents, presence of alkaloids and antifungal substances in the seed coat, etc. (Misra and Kanaujia 1973). Nair (1982) reported less number of fungi on seeds of *Luffa acutangula* during storage, as these absorb less moisture because of their thick and hard seed coat. Varietal differences concerning the susceptibility to fungal attack during storage have also been observed by Sheeba and Ahmed (1994), who recorded higher fungal incidence on seeds of fertiliser-responsive, high-yielding paddy cultivars than the traditional varieties.

Initial seed moisture, storage temperature, and RH play important roles in maintaining seed health and germination. Hence, harvesting the seed at the right stage of maturity is the first and most crucial step in maintaining its successive storability. As mechanical injuries promote invasion of pests and pathogens, care needs to be taken during harvesting/ threshing and all other post-harvest handlings to minimise any physical damage to the seed. Pre-storage seed treatments also help improve the storability of seed by protecting the seed from microbial attacks during storage and in the field upon sowing, thereby resulting in better seed germination and field stand. Lal et al. (1976) reported that the application of propionic acid and potassium metabisulphite was effective against *A. niger*, *A. flavus*, *Penicillium oxalicum*, and *Alternaria alternata* on wheat and maize grains, whereas acetic acid and propionic acid were effective against *A. flavus* and *Curvularia lunata* on groundnut kernels. According to Vaidya and Dharam Vir (1986; 1987), sodium metabisulphite and propionic acid checked the growth of *Aspergillus* and *Penicillium* spp. on groundnut kernels. Besides ensuring the seed quality at the time of storage, it is also important to maintain sanitation of the seed godowns by keeping it clean, sanitised, dry, cool, free from cracks and crevices, and adequately ventilated. The seed material should be packed in clean containers. Gunny (hessian) and cloth bags are sometimes reused for packing grain seeds in bulk. These must be disinfected, or appropriately fumigated to avoid contamination by the carry-over pathogens. The seed stores should be regularly checked for the development of any pests, and efficient remedial measures, such as fumigating, must be employed immediately to keep these under control. Disease and pest management of stored seeds, thus, require optimum storage conditions and deployment of such treatments (of seeds, godowns, and bags) which do not pose any health hazards to the seed handlers and users. (See chapter 'Seed Health: Testing and Management').

Planting material of horticultural crops, such as stems, roots, leaves, tubers, corms, rhizomes, suckers, grafts, etc., may carry many pathogens due to their high moisture content. These may cause diseases reducing their planting value. The pathogens present in the soil may also hamper the field establishment of such propagules. Adoption of an appropriate seed treatment technology can help reduce most of these problems with greater efficacy in disease control, less environmental pollution, low health hazards for the operators, and lesser use of workforce compared to later stage spraying, besides reducing the wastage of the chemicals.

8 Long-Term Seed Preservation

Long-term seed storage is most commonly used for conserving plant germplasm for future use and to maintain the wealth of biodiversity. For this, seeds are preserved at very low MC and low to very low temperatures in the Genebanks. Genebanks play a vital role in the conservation, availability, and use of plant genetic diversity for crop improvement. Maintaining viability, genetic integrity, and quality of stored seed samples and making them available for use even after decades of storage is the primary objective of genebanks (FAO 2014). Hence, seeds are dried to attain a glassy state (See chapter 'Seed Longevity and Deterioration' for more details on glassy state) and stored at low to sub-freezing temperatures to preserve germination for prolonged periods. Stocks are regenerated when germination falls below the stipulated standards. Hay and Whitehouse (2017) suggest that instead of planning regeneration of seed stocks based on initial germination, these may be based on seed storage experiments to identify which seed lots to test first and use sequential testing schemes to reduce the number of seeds used for viability testing, besides using tolerance tables. Different methods can be used for seed drying, such as equilibrating in a dehumidified atmosphere by storing seed with desiccants or using a dehumidifier chamber. The methods chosen will depend on the available equipment, number and size of the samples to be dried, local climatic conditions, and cost considerations. However, there is a limit to which drying can increase longevity. For long-term storage (Cromarty et al. 1982), therefore, seed samples should be dried to an equilibrium of 10–25% RH in a controlled environment of 5–20 °C, so the MC of seeds reaches $<5\%$ and are sealed in a suitable airtight container. These are stored at -18 ± 3 °C and relative humidity of $15 \pm 3\%$ for long-term storage of Base Collection (usually stored for up to 50 years). For longest-term storage, seeds in hermetically sealed containers are stored in liquid nitrogen canisters. For medium-term storage (10–15 years), samples are stored at 0–10 °C. Working collections can also be stored for 3–5 years at 5–10 °C. These collections are used for evaluation, multiplication, and distribution of the accessions for use. Active collections are usually maintained by multiplying the seeds of their accessions or periodic regeneration of the base collection. However, significant variations can be seen in longevity of seeds of different species maintained under similar conditions of long term storage (Walters et al. 2005).

Ultra-drying reduces seed moisture to 1–3% using desiccated forced air drying, heated drying, or freeze-drying. Kong and Zhang (1998) demonstrated that there was practically no difference in longevity when seeds were dried over silica gel by freeze-drying or heating to 50 °C, as long as the seeds were not over-dried below 1.5%. However, freeze-drying and heating treatments were more advantageous than drying over silica gel due to the faster speed at which seeds could be dried (10 times faster).

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