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REVIEW

Grain Hermetic Storage and Post-Harvest Loss Reduction in Sub-Saharan Africa: Effects on Grain Damage, Weight Loss, Germination, Insect Infestation, and Mold and Mycotoxin Contamination

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Abstract

Purpose The purpose of this study was to review the different hermetic storage (HS) systems used in Sub-Saharan Africa (SSA) and their effectiveness against the agents of storage quality deterioration.

Method Relevant studies on grain HS in SSA conducted in the past two decades for effectiveness against the agents of storage losses are reviewed. Specifically, the study comprehensively reviewed the effectiveness of HS technologies against insect-induced damage and weight loss, seed germination, insect infestation, and mold and mycotoxin contamination. Traditional grain storage methods and HS technologies used in SSA are reviewed, including those suitable for smallholder farmers and traders. Future developments and modifications to HS are also discussed.

Results Most grain HS studies are carried out in SSA where post-harvest storage losses are considered one of the world's largest. Scholarly studies compared the performance of HS against traditional technologies for storage periods of up to 7 months and a few extending to 1 year or more. Commonly studied HS technologies include hermetic layered bags and grain silos. In general, HS offers superior protection against the agents of grain deterioration for long-term storage compared to conventional storage technologies.

Conclusion HS technologies are highly effective in protecting stored grains from quantitative and qualitative storage losses and thus guarantee that stored grains can attract better prices and are safe and nutritious to the consumer.

Keywords Post-harvest losses · Grain storage · Hermetic storage · Smallholder farmers · Sub-Saharan Africa

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Nomenclature

SSA	Sub-Saharan Africa
PHLs	post-harvest losses
HS	Hermetic storage
HDPE	High-density polyethylene
PICS	Purdue improved crop storage bag
PP	polypropylene bag
SG	SuperGrain bag

Introduction

The world population will be over 9 billion people by the middle of the twenty-first century (UN, 2019), and food production must grow by up to 70% to meet the new food demand (Affognon et al., 2015; Binns et al., 2021; Hodges et al., 2011). Developing nations in Sub-Saharan Africa (SSA) and

South Asia will contribute the largest to this projected population rise and hence food demand (Hodges et al., 2011; Kumar and Kalita, 2017). Even with current populations, these nations are already struggling with many challenges such as low agricultural production and productivity. The challenge to feed the world will need redress amidst worsening climate crises, natural resource depletion, increasing urbanization, environmental degradation, and land demand for alternative uses. World leaders, scientists, and philanthropists are progressively engaged in rethinking possible strategies to achieve this goal amidst all challenges.

Among the options to meet the food demand are to (1) increase food production on existing land, (2) sustainably bring more land into agricultural production, and (3) make more food available through the global reduction of post-harvest food losses and food wastes. All these interventions demand the full awareness that any food security effort need not only be suitable but environmentally, socially, and economically sound, acceptable, and sustainable (Guenha et al., 2014; Movilla-Pateiro et al., 2020). Increasing food production on existing land can play an important role but will be constrained by the finite resources of land, water, and the biosphere (Elferink and Schierhorn, 2016; Godfray et al., 2010). Besides, bringing more land acreage into agricultural production may be unsustainable in the long term due to shrinking agricultural land and rapid urbanization (Bob, 2010) and can inevitably lead to biodiversity loss. An integrated approach should, thus, not only aim at increasing food production and productivity but should, together with other strategies, focus on reducing post-harvest losses (PHLs) through proper and sustainable post-harvest handling practices (Guenha et al., 2014; Silva et al., 2018).

While different crops are grown globally, grain crops are considered important in food security and nutrition as sources of vital dietary calories and proteins to consumers (Alonso-Amelot and Avila-Núñez, 2011; Mesterházy et al., 2020). Globally, cereal grains are the key sources of calories with rice, wheat, and maize being considered the most popular staple food crops in most developing countries (Kumar and Kalita, 2017). Due to its importance, cereal grains supply the calorie needs of over 60% of the population in developing countries (Awika, 2011). Like cereals, legume grains contribute about 33% of the global dietary protein needs (Vance et al., 2000). This is significant in developing economies where the majority of the population lacks adequate physical and financial access to protein sources of other origins. In SSA, maize, rice, wheat, millet, and sorghum are the most commonly cultivated cereal grains, with common beans, chickpea, cowpea, pigeon pea, and groundnuts being the most cultivated legumes (Raheem et al., 2021; Vanlauwe et al., 2019).

Despite the contribution of grains to food security and nutrition in developing countries, PHLs in the sector remain high. PHLs are measurable quantitative and qualitative food losses that occur at any point between crop harvesting and consumption due to several causes linked to physical, physiological, and environmental factors. These factors may include grain mechanical damage, heightened temperature and relative humidity, mold and mycotoxin contamination, invasion by pests (insects, rodents, birds), inappropriate handling, storage, and processing (Abass et al., 2014; Hengsdijk and De Boer, 2017). In SSA, quantitative grain PHLs are estimated at between 10 and 30% (APHLIS, 2020; Brown et al., 2013) and could reach up to 50% or more when considered together with quality losses (Rickman, 2002; Shee et al., 2019). On a global scale, about one-third of the food produced for human consumption, estimated at USD 1.0 trillion, is lost or wasted annually in PHLs (World Bank, 2011). In SSA, grains worth about USD 4 billion out of estimated annual grain production of USD 27 billion are reportedly lost annually as PHLs (World Bank, 2011). Among the causes of PHLs, grain storage losses are considered the main loss factor in developing countries (Kumar and Kalita, 2017), estimated at between 10 and 20% of stored commodities mainly resulting from insect pests (Philip and Throne, 2010). The causes of grain PHLs in storage include poor storage conditions, lack of proper storage infrastructure, high temperature, and relative humidity. These lead to mold development, high respiration rate, and increased insect activity, with negative consequences on the quality of stored grains.

Due to high incidences of storage insect pest infestations, many smallholder farmers in developing countries sell their grains shortly after harvest for fear of losses to storage pests (Mutungi et al., 2015). These farmers soon buy the grains at often relatively higher prices than sold during the lean seasons. When grains are not sold immediately after harvest, smallholder farmers manage insect pests using various forms of cultural practices and application of botanicals (Kamanula et al., 2010; Said and Pashte, 2015) or through the use of synthetic pesticides (Upadhyay and Ahmad, 2011). The use of botanicals such as wood ash, animal dung, and admixtures are often not very protective for long-term grain storage and become unsuitable when grain quantity becomes large (Mutungi et al., 2014). Despite its effectiveness, there is available scientific evidence linking synthetic pesticide residues in foods to health complications and environmental contamination (Dubey et al., 2008; Loganathan et al., 2011). Besides, the development of insect resistance (Benhalima et al., 2004; Chulze, 2010; Collins, 2006), lack of knowledge on proper applications and use (De Groote et al., 2013; Mutungi et al., 2014), high cost and unavailability (Tefera et al., 2010), and reduced grain quality in some cases have disadvantaged the use of synthetic pesticides for the preservation of grains during storage.

Alternative safe, effective, and eco-sustainable storage technologies that eliminate synthetic pesticide use without compromising grain quality have attracted the attention of scientists, medical practitioners, consumers, and policymakers to minimize storage losses due to insects. One such technology is the use of hermetic or airtight storage. HS use has attracted global interest and the attention of all stakeholders involved in the recent few decades (Baributsa and Ignacio, 2020). Due to their ability to store grains safely and for sufficiently long periods without the need to use synthetic pesticides (Baributsa et al., 2010; Carvalho et al., 2012; Kumar and Kalita, 2017), HS technologies have become popular for a wide range of commodities in Africa, Asia, and in South and Central America (Sudini et al., 2015). The success of the technology is due to the drastic elimination of oxygen (O_2) with a parallel build-up of carbon dioxide (CO_2) in the internal atmosphere due to the aerobic respiration of insects, grains, and fungi (Moreno-Martinez et al., 2000; Odjo et al., 2020). In such a modified grain atmosphere, insect death occurs either through hypoxia or desiccation (Moreno-Martinez et al., 2000; Murdock et al., 2012).

The success of any grain storage technology relies on its efficacy to protect the stored commodity from the agents of deterioration. These deteriorations include, among others, grain damage and weight loss, nutritional changes, grain moisture content changes, insect infestations, and mold and mycotoxin contamination. The degree of grain storage deterioration depends on the storage method used and storage conditions. HS technologies prevent or minimize stored grain quantity and quality deterioration, hence reducing storage losses. While HS has been in use since ancient times, its scientific research in SSA caught momentum in the past two decades or so. Numerous studies have demonstrated the effectiveness of different HS technologies for protecting stored grains under various storage conditions. However, there is a need to document evidence-based information on how HS technologies affect grain quality parameters in storage compared to traditional techniques as undertaken by research scientists in the past 20 years. The objective of this review paper was thus three-fold: first, discuss the factors responsible for grain storage losses in the context of SSA; secondly, describe the HS technologies commonly used for grain storage in SSA; and lastly, comprehensively review research studies conducted in the past two decades to demonstrate the effectiveness of HS technologies on grain quality.

Major Factors of Post-Harvest Storage Concern in Sub-Saharan Africa

Grain deterioration factors in storage consist of biotic and abiotic factors (Moses et al., 2015). The biotic factors are related to the living organisms in the grain ecosystem and include insect pests, rodents, birds, fungi, and the grain itself (Befikadu, 2014). In SSA, insect pests are considered the most significant biotic factor of storage concern (Midega et al., 2016; Njoroge et al., 2014). Abiotic factors include the non-living component of the grain ecosystem that affects the functioning of biotic components. These include temperature, relative humidity, intergranular gaseous levels, and grain moisture content (Moses et al., 2015). Moisture content and temperature are the two most important abiotic factors that significantly affect grain storage quality and shelf-life(Gonzales et al., 2009; Kumar and Kalita, 2017). Continuous and unfavorable interactions that occur over time between the biotic and abiotic variables cause grain deterioration (Moses et al., 2015), with the extent of interactions determining the degree of deterioration in storage.

Biotic Factors

Insect Pests

Stored grain insect pests are the most devastating biotic factor in storage grain deterioration (Moses et al., 2015) and can cause severe grain losses amounting to up to 40% of stored grains (Abass et al., 2014; Boxall, 2002; Bradford et al., 2018; Ognakossan et al., 2018; Tapondjou et al., 2002; Tefera et al., 2010). Most storage insect pest species are either beetle (Coleoptera) or moths (Lepidoptera)(Table 1), although there are some other types (Hodges and Maritime, 2012; Upadhyay and Ahmad, 2011). Both grubs and adult insects attack stored grains for beetles, while caterpillars are the destructive life stage among the moths (Upadhyay and Ahmad, 2011).

The severity of insect infestation in stored grains is a factor of the geography and climatic conditions and is a concern in the tropical and sub-tropical regions where the climatic conditions favor their rapid multiplication (Moses et al., 2015). In SSA, the maize weevil (*Sitophilus zeamais*) and the larger grain borer (*Prostephanus truncatus* Horn) are the most notorious and damaging storage insect pests known (Mutambuki et al., 2019; Vowotor et al., 2005), although several others also exist. *P. truncatus* is more destructive and can cause extensive grain damage amounting to over 30% dry weight loss in endemic situations (Cugala et al., 2007). *P. truncatus* first originated in Mexico and Central America and was accidentally introduced to Africa in the late 1970s where it has prevailed and thrived to date (Arthur et al., 2019).

The effect of insect pests on stored grains is both quantitative and qualitative. Insects cause considerable quantitative weight loss by penetrating the grain kernels, feeding on the endosperm and selectively removing the grain nutritious portion (Befikadu, 2014; Hodges and Maritime, 2012). In Niger, several grain crops lost between 7.4 and 83.9% of their original weight due to insect infestation after 6 months in storage (Baoua et al., 2015). In Zimbabwe, weight losses of maize due to insect pests were between 2 and 13% after 8 months of storage in traditional granaries (Giga et al., 1991). In

Table 1 Common insect pests of stored grains in SSA

Category	Common name	Scientific name	Commodities attacked	Mode of damage	Reference
Beetles	Larger Grain Borer	*Prostephanus truncatus*	Unshelled maize, dried cassava chips	Both larvae and adults bore into grains and feed, producing large quantities of dust.	Gueye et al. (2008); Taruvinga et al. (2014)
	Lesser grain borer	*Rhyzopertha dominica* (F.)	All cereals; Generally uncommon in maize	Both larvae and adults bore into grains and feed on the endosperm, producing large quantities of dust.	Taruvinga et al. (2014)
	Maize weevil	*Sitophilus zeamais* (Motschulksy)	Maize, sorghum, and rice	Fully grown larvae feed and pupate within the grain; Adults emerge, biting their way out of the grain, leaving a characteristic emergence hole.	Hodges and Maritime (2012); Taddese et al. (2020)
	Rice weevil	*Sitophilus oryzae* (L.)	Rice and cereal products	Both larvae and adults bore into the grain kernel. Can cause considerable damage in a short time.	Jayakumar et al. (2017)
	Bean bruchid	*Acanthoscelides obtectus*	Dried beans	Larvae cause damage by chewing their way into the grain.	CABI (2019)
	Cowpea weevil	*Callosobruchus maculatus*	Dried pulses	The larvae and adult stages are the primary cause of damage to the seed embryo.	
	Red flour beetle	*Tribolium castaneum* (Herbst)	Maize, groundnuts, rice, beans, peas, sorghum, and wheat	Both adult and larvae feed first on the germ and later on the endosperm. Usually found in poor storage conditions that allow pests to thrive.	Guenha et al. (2014); Taruvinga et al. (2014)
Moths	Angoumois grain moth	*Sitotroga cerealella* (Oliver)	All cereals	Larvae bore into the grain and feed on its contents, filling the resulting cavity with excreta. Infestations produce large amounts of heat and moisture, promoting mold growth.	Taruvinga et al. (2014)
	Rice meal moth	*Corcyra cephalonica*	Rice, maize, millet, and whole wheat	Larvae contaminate grain by producing large amounts of webbing and frass, which bind food together and make it unsuitable for sale or consumption.	
	Tropical warehouse moths	*Ephestia cautella*	All cereals	The larvae feed externally on grains. Most of the damage is contamination with large amounts of silk by the moth, accumulating fecal pellets, cast skin, and eggshells.	Shehu et al. (2010)

Ethiopia, wheat grains suffered substantial insect-induced damage of between 3.6 and 13.6% with corresponding weight loss of between 0.7 and 2.5% after 6 weeks of storage (Kalsa et al., 2019). As insects feed, grain moisture content increases due to the aerobic respiration process that causes qualitative grain loss through the development of molds (Befikadu, 2014). The heat generated due to the metabolic process causes an increase in grain temperature and hence increased reproduction rate of storage insects. As the population of insects increases, more moisture is produced in the grain, and the cyclic process continues, sometimes at even faster rates. Qualitative grain deterioration by insects is also through their excreta, dead insects, partial consumption of grains which reduce the quality and consumer appeal of the grain, and reduced nutritional content (Johnson, 2020; Stathers et al., 2020; Taddese et al., 2020).

Rodents and Birds

Rodents are notorious for invading stored grains irrespective of the grain storage period and can, like insect pests, affect both grain quality and quantity (Brown et al., 2013). In Kenya, rodents are the second most important cause of storage losses after insect pests, responsible for between 30 and 43% of the storage weight losses of maize (Ognakossan et al., 2016). When present in grain stores, rodents can consume daily food equivalent to 10% of their body weight (Mills, 1996). In East Africa, the main rodent species of post-harvest storage concern include the black rat (*Rattus rattus*), the house mouse (*Mus musculus*), and the Natal multimammate mouse (*Mastomys natalensis*) (Makundi et al., 1999). These have become highly successful commensal invaders of grain stores with extreme adaptability and a high procreation rate. *R. rattus* and *M. musculus* inhabit houses and storage structures, while *M. natalensis* moves from the field to storage structures in search of food whenever there is scarcity in the field (Ognakossan et al., 2016).

There are remarkably few studies in SSA quantifying grain post-harvest storage losses due to rodents (Brown et al., 2013). A study in Kenya reported cumulative weight losses of 2.2–6.9% and 5.2–18.3% in shelled maize and dehusked cobs respectively after 3 months of storage due to *R.*

rattus(Ognakossan et al., 2016). Apart from causing direct physical weight losses due to feeding, rodents in grain stores can lead to several other storage challenges such as damage to storage structures like sacks and buildings and contamination of grains with urine, hair, and fecal droppings (Brown et al., 2013; Ognakossan et al., 2018). Grains contaminated by rodent droppings may harbor pathogens rendering them unsafe and unfit for human consumption (Hodges et al., 2014). Another problem imposed by rodents is that their urine may participate in the proliferation of molds due to increased water activity of the grains, and rodent feeding itself could facilitate the dissemination of fungal spores (Ognakossan et al., 2018).

Bird infestation of grain stores in SSA is rarely a problem but can be a concern when doors, windows, and ventilators are left open, providing easy access to the interior of stores. The bird species of concern in grain storage facilities are predominantly the same species that cause problems in domestic and commercial centers of many rural and urban areas (McCarthy, 2003). In SSA, bird species commonly known to invade grain stores are sparrows (*Passer domesticus*), pigeons (*Columbia livia domestica*), and chicken (*Gallus gallus* L.). Birds cause deterioration of stored grains through grain consumption, contamination with excreta, and the introduction of mites (Mills, 1996).

Mold and Mycotoxin Contamination

Molds (fungi) responsible for grain deterioration consist of two main groups based on their predominance at different crop growth stages and harvest, affected by environmental conditions. The first group is the field fungi which colonize ripening grains on field standing crops during the crop maturation stage. Examples of field fungi include *Alternaria* and *Fusarium*(Mannaa and Kim, 2017). The second group is the storage fungi which may be present in minute numbers before harvesting but increase substantially during storage due to favorable environmental conditions (Mannaa and Kim, 2017). Storage fungi mainly consist of *Aspergillus* and *Penicillium*(Bradford et al., 2018).

Mold contamination of stored grains can cause undesirable qualitative and quantitative changes. These changes include grain discoloration, heating, dry matter loss, increased fatty acid content, mycotoxin production, loss of germination, and degradation of lipids and proteins (Magan and Aldred, 2007). Grain contamination by certain molds is also considered a serious food safety concern in the tropical and sub-tropical regions where the ambient relative humidity is high. This is due to the carcinogenic nature of the mycotoxins produced by these molds (Kaaya and Kyamuhangire, 2006). Mycotoxins are secondary metabolites produced by certain fungal species, mostly *Aspergillus*, *Fusarium*, and *Penicillium*(Mannaa and Kim, 2017), and are toxic to humans and animals (Bradford et al., 2018). Among the mycotoxins, aflatoxin, ochratoxin, deoxynivalenol, zearalenone, fumonisin, trichothecenes, and patulin significantly contaminate stored grains (Wagacha and Muthomi, 2008). Mycotoxin contamination by aflatoxin and fumonisin renders grains unsafe for human consumption (Tefera, 2012). Consumption of aflatoxin-contaminated foods results in aflatoxicosis that may cause death in extreme cases through liver inflammation (Tefera, 2012).

Mold and mycotoxin contaminations are influenced mainly by two environmental factors: temperature and relative humidity (Moses et al., 2015). Relative humidity of at least 70% promotes mold growth in grains (Ng'ang'a et al., 2016a). Relative humidity at the grain surface layer is a factor of moisture content of the grains in equilibrium with a relative humidity of 70%, which for most grains is about 14% (Hodges and Maritime, 2012). When moisture content increases to 15–19%, molds of *Aspergillus* spp. and *Penicillium* spp. grow. This causes an increase in the grain respiratory activity (Magan and Aldred, 2007), which leads to an increase in temperature due to the aerobic respiration process resulting in grain heating, and hence spoilage. It is thus imperative that grains are stored at a moisture content of at most 14% to avoid mold growth and mycotoxins.

Abiotic (Physical) Factors

The principal physical factors which interact to influence stored grain microenvironment include temperature, relative humidity, moisture content of the stored grain, and gaseous concentrations (especially oxygen and carbon dioxide in the grain interstitial environment). The first three factors are discussed in this section while gaseous concentrations are discussed under the principle of grain hermetic storage.

Temperature and Relative Humidity

Proper temperature and relative humidity management are considered the two most important management strategies that can be used to protect stored grains from the devastating effects of insect pests and molds. Most storage insect pests thrive in an optimal temperature range of between 25 and 34 °C for most species and between 15 and 30 °C for mold development (Moses et al., 2015; Taruvinga et al., 2014). Most SSA countries fall within this temperature range and suffer huge grain storage losses to insect infestations exacerbated by poor storage practices and infrastructure in these regions. Outside these temperature ranges (colder or hotter), the development of insects and molds is constrained despite the tolerance exhibited by certain species and life stages of certain pests (Loganathan et al., 2011).

Relative humidity, the percentage of water vapor in the air between the grains at a given temperature, represents the equilibrium between the air humidity and the grain moisture content. The relative humidity of the intergranular air is responsible for determining which living organisms can develop in stored grains (Mills, 1996). Relative humidity above 65% facilitates the development of mold and insect pests which may cause grain deterioration (Taruvinga et al., 2014). There is a direct linear relationship between grain temperature and relative humidity: an increase in grain temperature causes an increase in grain relative humidity (Devereau et al., 2002). High temperature and relative humidity regimes that characterize the tropical regions of SSA are favorable for insect growth and development, shortening their life cycle. This results in increased insect pest populations (Phophi et al., 2020; Van Dyck et al., 2015). Besides insect infestation, the high temperature and relative humidity in SSA increase the susceptibility of stored grains to mycotoxin contamination (Magan et al., 2011).

Moisture Content

Moisture content is the amount of moisture per unit weight of grain sample. The amount of moisture present in grains determines the extent of physical, biological, and biochemical activities in stored grains (Suleiman et al., 2013). As dry grains are hygroscopic, they may gain or lose moisture in traditional storage systems due to fluctuations in the external relative humidity environment (Diarra and Amoah, 2019). Grains at harvest have high moisture content in the range of 16–20% or more and must be quickly dried to at most 14% before storage to prevent deterioration (Magan et al., 2010). When inadequately dried before storage, grain temperature will rise due to the respiration process of the grains resulting in the development of spoilage molds (Magan et al., 2010).

The moisture content of stored grains has a key role in deterioration, and each grain has recommended storage moisture content without significant quality deterioration. The moisture content of dry grain varies between 6 and 15% depending on the type of grain and duration of storage (Taruvinga et al., 2014). Also, at a given relative humidity, insect pests prefer grains with higher moisture content, probably because of the soft texture nature of these grains (Pixton and Warburton, 1971). As a rule of thumb, the higher the moisture content of stored grains, the greater the degree of susceptibility to deterioration to insect pests and mold deterioration.

Conventional Grain Storage Technologies in Sub-Saharan Africa

There are several traditional methods used for grain storage in SSA. These mainly include jute bags, cloth bags, woven polypropylene (PP) bags, and woven baskets. There are also several others. These are extensively described in the work of Mobolade et al. (2019). The woven PP bag is the most commonly used traditional grain storage method globally (Nduku et al., 2013). These bags, which mostly come in sizes ranging from 25 to 100 kg, are widely used by smallholder farmers due to their availability, affordability, and convenience in handling and use (Mobolade et al., 2019). The limitation of the traditional storage methods such as the woven PP bags is that they permit the exchange of air and moisture between grains and the ambient environment. This allows the biotic organisms enclosed in the grain to continue their metabolic life unrestricted unless a control measure such as the use of synthetic insecticides is in place. HS has come in place to fulfill this gap by restricting interactions between the ambient environment and internal grain atmosphere.

Principle of Grain Hermetic Storage

HS is credited for long-term and intermediate storage of grains without synthetic insecticides due to their ability to create a hostile internal environment detrimental to the growth, development, reproduction, and survival of insect pests within the stored grains. This is because HS provides a barrier that limits O_2 and moisture exchange between the grain's internal atmosphere and external environment (Odjo et al., 2020). The effectiveness of HS depends on the integrity of the hermetic seal, the nature of the stored commodity, the type and prevalence of insect pests, and the mechanical strength of the barrier material used (Njoroge et al., 2014).

HS that relies on the grain ecology to create low O_2 with a parallel high CO_2 atmosphere is a form of a biogenerated modified atmosphere, also referred to as Organic HS (Cheng et al., 2013; Villers et al., 2006). The low O_2 and high CO_2 environment are due to the physiological process of aerobic respiration of insects, grains, and molds in the sealed structures of HS (Calderon and Navarro, 1980; Jonfia-Essien et al., 2010; Quezada et al., 2006; Sanon et al., 2011; Tubbs et al., 2016; Williams et al., 2014). In order of ranking, insects are the largest consumer of enclosed O_2 followed by molds and lastly grains (Moreno-Martinez et al., 2000). The grain respiration process accounts for a minimal drop in O_2 and a rise in CO_2(Baoua et al., 2012). When O_2 level is reduced to 3% v/v or below, insects stop feeding and eventually die due to hypoxia (Moreno-Martinez et al., 2000). Besides the death of insects, fungal development also ceases at such low O_2 levels (Moreno-Martinez et al., 2000).

Organic HS is the most common form of HS in developing countries (Villers et al., 2006) since it relies on the grain ecology alone to control insect pests. In specialized applications requiring rapid disinfestation, O_2 levels can be quickly decreased through (1) the application of a high vacuum sufficient enough to eliminate all stages of insect pests (termed vacuum HS); and (2) through purging with an external CO_2 gas (termed gas-hermetic fumigation). In either case, the O_2

levels can be quickly reduced to at most 2% in a short time (Navarro et al., 2003; Villers et al., 2006).

The role of reduced O_2 levels in protecting stored grains from insect pests is two-fold. The first role is that O_2 provides a basis upon which oxidative metabolism occurs to provide energy without which growth, reproduction, and survival become difficult for the living organisms responsible for grain deterioration. The O_2 enclosed in the biogenerated interstitial grain atmosphere in HS is consumed according to the general respiration equation as shown in Eq. (1). The depletion in O_2 levels rather than the CO_2 accumulation is responsible for the constrained development and survival of insect pests in the stored grains (Bailey, 1965; Murdock et al., 2012). The CO_2 levels attained in a biogenerated HS, usually at most 20%, may not cause insect mortality but may impose behavioral changes in certain insects (Willis and Roth, 1954). Despite the limited effects of CO_2 levels in Organic HS on insect mortality, the synergistic effects of low O_2 levels and elevated CO_2 levels are more effective in controlling insects compared to the effect of the individual gases (Calderon and Navarro, 1980; Cheng et al., 2013).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Energy \tag{1}$$

The second role of reduced O_2 in insect pest control in hermetic grain storage is that it serves as a supply of metabolic water for the insects as shown in the respiration process in Eq. (1). This metabolic water is essential to sustain the vital life processes of insects. At limiting O_2 levels of HS, this source of metabolic water is interrupted (Murdock and Baoua, 2014). Due to this, enclosed insects or their life stages gradually desiccate and die since they continue to respire, losing water from their tissues. The early instars of the insect pest life stage are particularly more vulnerable to asphyxiation and desiccation as they are metabolically more active (Murdock et al., 2012).

The Contribution of Grain Hermetic Storage to Food Security

Improved storage such as the use of HS can affect all the four internationally recognized pillars of food security of availability, access, utilization, and stability (Napoli et al., 2011). Storage of grains in HS containers prevents grain insect infestations and moisture loss due to environmental relative humidity changes, all responsible for physical grain losses if unchecked. Storage in HS guarantees food security by causing improvement in food availability through reduced physical food losses (Adeola, 2020; Tefera, 2012). This effort can lessen the burden to improve local food availability through food imports and food aid donations at the national and regional levels. Reduced post-harvest storage losses also help improve grain supply in the markets relative to the demand, resulting in increased food access by the consumers. This may result in food price reductions on the one hand and improved farmers' incomes due to superior grain quality sale on the other, empowering farmers to gain financial access to other foods which they do not physically produce (Delgado et al., 2021).

Besides improved food availability and access, HS of grains helps guarantee food utilization by consumers through preservation of the stored grain nutritional values such as calories, proteins, and vitamins (Sheahan and Barrett, 2017), in addition to micronutrient quality preservation. Grain storage loss reduction is also critical in improved food safety due to the management of fungal or pest infestations that would otherwise result in consumer health implications through the consumption of otherwise contaminated foods. In so doing, there is an improvement in food utilization by the consumer. HS of grains also contributes to improved food price stability due to an increase in the amount of stored food, even during the crop off-seasons(Bendinelli et al., 2020).

Forms of Hermetic Storage Commonly used in SSA

HS of grains is used in several forms to meet the different user scales and needs. Despite the diversity, they work under the same principle as discussed in the previous section. As discussed in the following section, these include the hermetic layered bags, metal and plastic silos, plastic drums, Cocoons, and other containers.

Hermetic Layered Bags

Hermetic layered bags are one of the many methods of airtight storage based on a biogenerated modified atmosphere. Most hermetic bags used for grain storage consist of two main components: (i) an inner (single or double) liner of high-density polyethylene (HDPE) bag, and (ii) an outer bag. The inner HDPE liner consists of a thin, transparent, and low permeability multi-layer plastic that limits the permeability of gases so that a low O_2 environment is created and maintained at levels that hinder the development of all stages of insect pests. When the HDPE liner is pierced or damaged, the bag loses its protective integrity. In the case of bags with double inner HDPE liners, the second liner provides extra safety should one of the liners become damaged. The outer bag, usually a woven PP or jute bag, offers extra strength and protection during handling.

There are two main forms of hermetic layered bags used for grain storage in SSA. These are the Purdue Improved Crop Storage (PICS™) bag and the SuperGrain™ (SG) bag. There has been widespread adoption of both PICS bags and SG bags in West and Central Africa due to their efficacy against storage pests, but also due to their low cost, little space requirement, durability, and ease of manufacture and use (Baributsa et al., 2010; Ndegwa et al., 2016). Despite their effectiveness, hermetic bags have some limitations which include susceptibility of HDPE liners to physical damage and perforations from certain insect species and rodents (Chigoverah and Mvumi, 2016; De Groote et al., 2013; García-Lara et al., 2013; Manandhar et al., 2018).

Purdue Improved Crop Storage Bag

PICS bag is a trademark hermetic layered bag originally developed in the late 1980s by Scientists from Purdue University with financial support from the United States Agency for International Development (USAID) in a Bean/Cowpea Collaborative Research Support Program (Moussa et al., 2014; Murdock and Baoua, 2014). Initially developed to manage insect pests in cowpea grains in West and Central Africa (Murdock et al., 2012), PICS bag successes, utilization, and adoption have extended to several grain commodities spanning territories beyond the Central and West Africa corridors. It consists of three-layered plastic bags. These consist of (1) two 80 μm inner HDPE bags, one surrounded by the second to create a low permeability seal, and (2) an outer bag made of woven PP bag which endows mechanical strength to the two inner HDPE bags and the storage bag as a whole (Baributsa et al., 2010; Murdock and Baoua, 2014). For PICS bags to be effective in controlling insect pests, each of the two inner liners should have a minimum thickness of 80 μm as liners less than this have proven to be less effective (Sanon et al., 2011).

PICS bags are considered the most cost-effective grain storage option for smallholder farmers in Africa (Ibro et al., 2014) and is promoted and marketed in the continent at a retail price of about USD 2–3 per bag (Baoua et al., 2018; Murdock and Baoua, 2014). PICS bags come in three different sizes of 25 kg, 50 kg, and 100 kg bags in SSA (Baributsa and Ignacio, 2020; Jones et al., 2011).

SuperGrain Bag

SG bags were initially developed for rice seed storage in a 5-year research project of the International Rice Research Institute in the Philippines (Villers et al., 2006). It has since been used to store other grain commodities. They are produced commercially by GrainPro Inc. in the Philippines and share a very close similarity to the PICS bag. While the PICS bag consists of two inner HDPE liners, the SG bag consists of a single HDPE liner having a thickness of about 78 μm, surrounded by an outer woven PP bag. SG bags are marketed in capacities ranging from 25 kg to 100 kg with prices ranging between USD 3 to 5 for 90 kg bags (Ndegwa et al., 2016).

Despite the registered success of SG bags in protecting stored grains, its protective action can be compromised in the presence of some species of insects such as the *P. truncatus*(Chigoverah and Mvumi, 2016; De Groote et al., 2013), due mainly in part to the perforations of the single HDPE liner by certain species of insect pests. Under such a circumstance, single-use for one season is recommended. Due to this, a more recent variant of the SG bag (SGB-IV R™) has been introduced with superior HDPE characteristics of greater toughness and puncture resistance while still retaining the original 78 μm thickness (De Bruin et al., 2012; García-Lara et al., 2013).

Other Hermetic Layered Bags

While the PICS and the SG bags are the two most common forms of hermetic layered bags used in SSA, several other brands have emerged in the recent past by either innovating or imitating pre-existing bags. These include the Elite bags and the AgroZ® bags, all manufactured in East Africa. AgroZ bags are double-layered (one 90 μm co-extruded inner liner combining HDPE and metallocene linear low-density polyethylene surrounded by an outer woven PP bag) bags developed and distributed by A to Z Textile Mills Ltd in Tanzania (Baributsa and Ignacio, 2020). Elite hermetic bags consist of a triple layer similar to PICS bags manufactured by Elite Innovations (K) Ltd based in Kenya.

Metallic Silo

A metallic silo (Fig. 1) is an airtight cylindrical structure made of a galvanized iron sheet to protect grains from post-harvest storage losses (Tefera et al., 2010). The metallic silo technology is proven to be very effective for considerable storage periods, offering protection to stored grains from not only insect pests but also rodents and birds (Chigoverah and Mvumi, 2016; De Groote et al., 2013; Kumar and Kalita, 2017; Tefera et al., 2010). Compared to the hermetic bags, metallic silos are physically stronger and offer superior grain protection for a much longer duration. The metallic silo first originated from Central America where the POSTCOSECHA (the Spanish word for post-harvest) program promoted its use in Central American countries from the early 1990s to 2000s (Hellin et al., 2008). However, one of the concerns regarding the use of metallic silos was the continued treatment of stored grains with phostoxin, a highly toxic grain fumigant, to offer extra protection (Yusuf and He, 2011). In SSA, the use of grain fumigants in many countries is, by law, restricted to licensed fumigation companies. To ensure a rapid depletion in O_2 levels, candles are lit and placed in metallic silos before sealing the top lid (Mubayiwa et al., 2021). This practice used in SSA has demonstrated that there is no need to use phostoxin fumigant in metallic silo grain storage.

Despite their effectiveness in reducing grain storage losses, metallic silos have some limitations that include (1) high

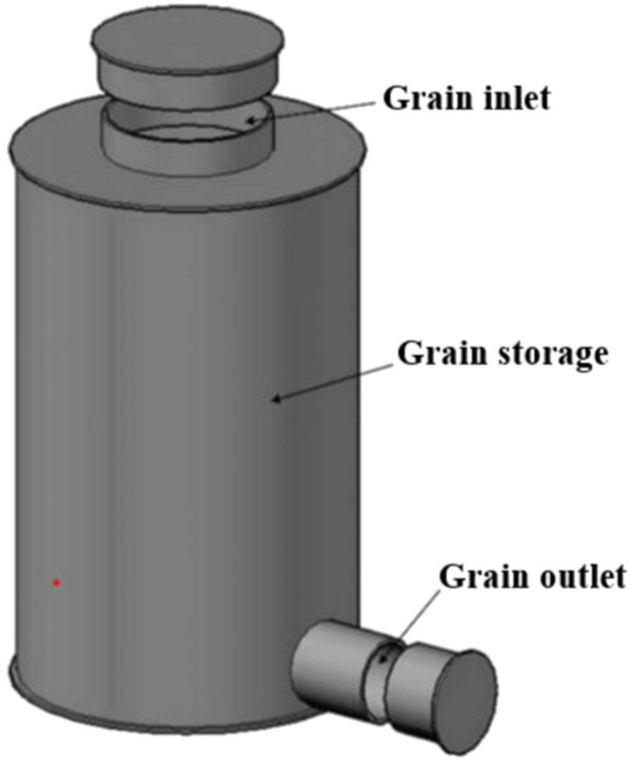

Fig. 1 Metallic silo used for grain storage in developing countries (Manandhar et al., 2018)

initial costs compared to the hermetic bags, (2) limited availability of galvanized iron sheets used for their manufacture, and (3) a limited number of trained artisans for their construction (Chegere et al., 2020; De Groote et al., 2013; Gitonga et al., 2013). Besides, failure to ensure hermetic seal during manufacture or improper usage may significantly jeopardize their protective integrity (Chigoverah and Mvumi, 2016; Manandhar et al., 2018). Due to these constraints, the adoption and use of metallic silos for grain storage in SSA have been relatively low to date.

Plastic Silo and Plastic Barrel

Like metallic silos, the plastic silo is used in many parts of SSA for grain storage. They may have the same design as the metallic silo with an inlet or outlet hole; plastic barrels commonly used for water harvesting are also frequently used for airtight grain storage in some communities (Abass et al., 2018). They can be made airtight like the hermetic bag or the metallic silo. While effective for grain storage, plastic barrels have other competing uses in water storage and are often considered expensive for smallholder farmers' grain storage (Ibro et al., 2014).

Despite the effectiveness of the silos and barrels for grain storage in smallholder farmer subsistence settings, containers need to be filled with grains to be effective (Covele et al., 2020). Smallholder farmers, however, produce a small quantity of grains that may not fill the larger size containers to ensure hermeticity. This is not necessary in the case of the hermetic bags.

Grain Cocoon

Grain Cocoon™ is a commercially available large-scale hermetic device with flexible liners used for grain storage without synthetic pesticides (Villers et al., 2006). The device is a large plastic bag that consists of two plastic halves joined together using an airtight zipper following loading of the device with bags containing grains. Grain Cocoon consists of a flexible UV-resistant polyvinyl chloride that guards against attack by rodents and prevents the exchange of air and moisture between the stored grains and the external environment. It can be used multiple times for many years under very harsh climatic conditions without getting damaged easily.

Like the SG bags, Cocoons are manufactured and distributed by GrainPro Company in the Philippines. The effectiveness of Cocoons for grain storage protection is reported, but scientific documentation of their performance in comparison with other storage methods is scanty (Chigoverah et al., 2018). A study in Ghana on the storage of cocoa beans (Jonfia-Essien et al., 2008; Jonfia-Essien et al., 2010) and Zimbabwe on maize storage (Chigoverah et al., 2018; Chigoverah et al., 2016) are some of the few documented studies in SSA on the use of Cocoons for grain storage. In all cases, they were highly effective for the protection of stored grain quality. In Sri Lanka, the use of Grain Cocoon for soybean storage was highly effective for 8 months (Gunathilake, 2020).

Alternative Hermetic Containers

While hermetic bags and silos are the common forms of HS commercially marketed for smallholder grain storage in SSA, there exist alternative containers that can equally be suitable (Williams et al., 2017). These include, among others, recycled plastic bottles, jerry cans, and metal drums. Plastic bottles, usually used water and beverage bottles, with most being small in capacity, are mainly suitable for seed storage (Odjo et al., 2020). This is beneficial as seeds are usually kept in small quantities for smallholder farmers compared to the harvest. Due to this, plastic bottles function as alternative storage containers in some areas. They tend to be small in size and are generally available, free of charge, in almost all urban and rural areas of SSA. While plastics remain an environmental nuisance in Africa, their utilization as alternative grain storage units can offer an environmental relief. Used empty oil drums for grain storage among smallholder farmers are also noticeable in some areas in SSA. However, these may provide an incomplete airtightness unless treated with a sealing material (Mann et al., 1999).

Advantages and Disadvantages of Hermetic Storage Systems

With HS, the quality of stored grains can be maintained longer for use as seeds or grains compared to traditional open storage systems such as the woven PP bags. The O_2-deficient and CO_2-enhanced atmosphere created in HS offers an advantage by providing an unfavorable environment for the development and survival of insect pests without the use of insecticides. Through this, insect infestation is eliminated, maintaining grain integrity of germination, moisture content, damage, weight loss, etc. for several months (Guenha et al., 2014; Villers et al., 2008). By protecting the quality of stored grains for longer, farmers can keep their stored commodities longer and earn higher incomes through sales during lean seasons (Guenha et al., 2014; Navarro et al., 1994). Besides, the use of HS guarantees the food security status of smallholder farming households.

HS use is also a relatively cheap grain storage method since it eliminates the need for synthetic insecticides or fumigation, offering significant economic and environmental benefits. The rapid adoption and use of HS in SSA can be linked to the increasing awareness of the dangers of synthetic pesticides and the demand by consumers for safe, environmentally friendly, and sustainable storage technologies. Some HS units, such as the silos, offer advantages through rodent protection, ease of installation and use, and the ability to be used for several years without damage. In addition to the above, HS is used to store products without the growth of mycotoxins such as aflatoxin in corn and peanut and ochratoxin in coffee (Nyarko et al., 2021; Villers et al., 2008).

Despite their effectiveness, some HS systems are highly susceptible to physical damage. This damage may occur due to the puncture of the inner HDPE liners by sharp objects or careless handling. Other sources of damage include abrasions and perforations due to certain insect pests and rodents (De Groote et al., 2013; García-Lara et al., 2013). These punctures and other physical damage breach the protective integrity of the hermetic seal and hence useful life of HS systems. The problem of physical damage to HS systems is more common in HDPE liners of HS layered bags. Some HS systems, such as the silos, have high initial costs and require knowledge and skills to construct and operate for them to be effective (Manandhar et al., 2018).

Effects of Hermetic Storage on Different Grain Quality Parameters

Effect on Grain Damage and Weight Loss

Grain damage refers to the visual physical evidence of deterioration in grain characterized by a hole, crack, or discoloration (De Groote et al., 2013). It is considered a more qualitative than quantitative grain assessment criterion usually reported as a percentage of damaged grains (Boxall, 2002). Grain damage is an important quality parameter as it influences the consumers' willingness to buy grain and the price payable (Compton et al., 1998; Mishili et al., 2011). Other qualitative factors that affect consumer grain buying choice include live insect pests, dead pest remains, and insect excreta on produce. Grain weight loss, meanwhile, is the disappearance of otherwise edible food, usually expressed as a percentage weight loss (Boxall, 2002; De Groote et al., 2013). Weight loss of grains during storage occurs due to several factors related to loss of mass and moisture. Moisture weight loss may result from relative humidity differences between grains and the ambient environment, evaporation occurring as the grain tries to equilibrate with the ambient relative humidity (Walker et al., 2018). Mass weight loss is attributed mainly to pests (insects, rodents, and birds) feeding on the grains, fungal infestation, and grain metabolic activity (Covele et al., 2020). However, weight loss due to grain metabolic activities is negligible (Baoua et al., 2014b).

HS has the potential to keep stored grain damage and weight loss at levels comparable to that of insect-free grains (De Groote et al., 2013; Martin et al., 2015), partly due to its ability to eliminate or minimize the devastating actions of insect pests. This effectiveness is attributed mainly to reduced O_2 levels inside HS devices which bring about behavioral changes in insects besides reduced growth, development, and reproduction. These limitations help prevent insect multiplication in hermetically stored grains (Chigoverah and Mvumi, 2016; Murdock et al., 2012). Besides, the ability of HS to limit relative humidity changes of grains against external changes helps prevent weight loss of stored grains. Several scholars have studied the effectiveness of HS in preventing grain damage and weight loss with successful results, retaining the quality and quantity of grains following long periods in storage.

In the study of the effectiveness of two different HS technologies on grain damage and weight loss, García-Lara et al. (2020) stored artificially infested maize grains in specialized hermetic containers: plastic hermetic silo (Bioxilo™) and plastic hermetic bag (sBag™) for 12 months. These were compared with storage in woven PP bags. Grains stored in woven PP bags recorded the highest degree of damage, with 51% and 60% total grain damage at 8 and 12 months respectively. In contrast, a minimal degree of grain damage of less than 10% occurred in grains stored in plastic hermetic bags and hermetic silos after 8 months. The 1000-kernel weight was unchanged after 8 months in hermetically stored grains while it decreased substantially in the traditional woven PP bag (12.8%).

Several other scholars have demonstrated the protective action of HS against the damaging effects of insect-induced grain damage and weight loss in stored grains (Atta et al., 2020; Baoua et al., 2014a; Baoua et al., 2012; Somavat et al., 2017; Yakubu et al., 2011). Table 2 shows the comparison of HS against traditional storage technologies on grain damage and weight loss. While treatment with synthetic insecticides may protect stored grains against insect-induced damage and weight loss, insecticidal potency is known to wear out with time (Mubayiwa et al., 2021; Mutungi et al., 2014). Due to this, insect re-infestation occurs later in storage which leads to profuse grain damage and weight loss.

Effect on Seed Germination

Access to good quality seeds is the foundation of smallholder farmer crop production in developing countries where at least 90% of cultivated crops depend on farmer-saved seeds (Mutungi et al., 2015; Neate and Guei, 2010). The private seed companies in developing countries tend to concentrate on hybrid seed production targeting affluent farmers who can afford to pay for new seeds every planting season. Smallholder farmers, however, are constrained by resources and may not be able to pay for these seeds and should therefore be able to store a portion of their harvested open-pollinated seed varieties to guarantee next season planting.

The time difference between crop harvesting and the next planting season is usually long, sometimes lasting several months; this may necessitate grains destined for use as seed to be stored well to guarantee high germinability in the next planting season. Several factors may compromise the ability of stored seeds to germinate such as natural aging, seed exposure temperature, insect infestation and seed damage (Martin et al., 2015), and relative humidity and seed moisture changes during storage (Guberac et al., 2003; Martin et al., 2015; Mutungi et al., 2015; Njoroge et al., 2014; Silva et al., 2018). All these factors are negatively correlated with seed germination. Insect pests are known to target the nutrient-dense portion of stored grains and thus destroy the embryo while feeding, reducing the seed germination potential and vigor of such planted seeds (Baoua et al., 2014b; Baributsa et al., 2017; Vales et al., 2014). High relative humidity of at least 80% causes fungal invasion of stored grain; proliferation of fungal spores in storage results in loss of seed viability and seedling vigor (Mutungi et al., 2014). Besides, seed germination may be severely affected by the complex changes resulting from increased heat and moisture due to the grain metabolic processes.

The type of storage is another factor that affects the germination capacity and vigor of stored seeds. Grains stored in different forms of HS containers have been shown to maintain their germination potential higher and longer than those in conventional non-hermetic counterparts (Anankware et al., 2012; Bakhtavar et al., 2019; Ellis and Hong, 2006; Freitas et al., 2016; Sudini et al., 2015). Table 2 shows the comparisons of hermetic and non-hermetic storage of grains on seed germination. From this, it is easily noticeable that hermetically stored grains preserve seed germination better than traditional storage practices. HS retains or minimizes decline in the germination of stored seeds by controlling insect multiplication and protecting against insect-induced damage during storage, thus promoting the ability of stored seeds to maintain their viability (Martin et al., 2015; Vales et al., 2014). Besides, HS protects stored seeds against fluctuating external relative humidity that would otherwise affect seed germinability.

Effect on Insect Infestation

The success of HS, perhaps, is its ability to minimize insect growth and multiplication in stored grains without synthetic insecticides. The technology is thus not only environmentally friendly but also cost-effective for smallholder farmers in developing countries as they do not have to buy grain insecticides. The biogenerated O_2-depleted and CO_2-enriched modified atmosphere causes insect mortality due to hypoxia and desiccation. In so doing, the insect population cannot grow in hermetically stored grains. Not only do O_2 and CO_2 changes cause insect mortality in hermetically stored grains, but also cause a cessation in egg production as well as larval and pupal development responsible for sustaining future pest populations (Amadou et al., 2016). Scholarly studies have shown HS technologies to be superior to conventional storage in protecting against stored grain insect infestations.

Freitas et al. (2016) studied the effectiveness of storing common beans in hermetic silo bags and used plastic bottles on common bean weevil infestation during 120 days of storage. There was no increase in the level of insect infestation by *Acanthoscelides obtectus* pests in grains stored in HS (silo bags and plastic bottles) during 120 days of storage. In contrast, infestation in non-hermetic glass containers increased by 54% after 120 days.

Baributsa et al. (2020) evaluated the performance of five post-harvest storage methods for maize grain storage during seven months in Benin. Naturally infested grains were stored in different hermetic bag brands (PICS bag, AgroZ bag, SG bag) and non-hermetic bags (woven PP bag and ZeroFly bag which is an insecticide-treated bag). Grains used in the experiment had a mean initial infestation of 52.5 insects per 500 g of grains. After 7 months of storage, there were no live insect pests in any of the HS bags investigated. In the woven PP and ZeroFly bags, however, live insect populations ranged between 1.8 and 5.3 insects per 500 g for *S. zeamais*, *R. dominica*, *T. castaneum*, and *Cryptolestesferrugineus* insect pests. Even though the ZeroFly storage is pre-treated with insecticides, it was unable to control insect infestations during storage.

Table 2 Comparison of different grain storage methods on grain damage, weight loss, insect infestation, and seed germination following storage for different durations

Commodity	Storage type	Grain conditions	Storage duration	Grain damage	Weight loss	Insect infestation	Seed germination	Reference
Bambara groundnuts (*Vigna subterranea* (L.) Verdc.)	PICS bag	Heavily infested grains	7 months	Unchanged	Lost 1.5% of weight	Mean of 2.4 adult insects per 500 g	− 2.4%	Baoua et al. (2014a)
		Lightly infested grains		Unchanged	Gained 1.8% of weight	No live adult insects per 500 g	− 1.2%	
	PP bag	Heavily infested grains		+50.9%	Lost 7.6% of weight	Mean of 309 adult insects per 500 g	− 89.1%	
		Lightly infested grains		+13,217%	Lost 19.0% of weight	Mean of 251.2 adult insects per 500 g	− 35.5%	
Maize (*Zea mays* L.)	PICS bag	Naturally infested grains	6.5 months	Unchanged	+0.8%	∇ 8.9-fold	− 3.5%	Baoua et al. (2014b)
	Woven PP bag			Δ 6.1-fold	-21.5%	Δ 10.3-fold	− 29.6%	
Mung beans (*Vigna radiata* [L.] Wilczek)	PICS bag	Naturally infested & uninfested grains	6 months	Unchanged	Unchanged		− 11.5%	Mutungi et al. (2014)
	Woven PP bag	Uninfested grains		Δ 1.9-fold	Δ 24.2-fold		− 45.3%	
		Artificially infested grains treated with Actellic Super dust		Δ 1.6-fold	Δ 20.8-fold		− 48.6%	
		Artificially infested grains		Δ 2.1-fold	Δ 27.5-fold		− 61.2%	
Pigeon peas (*Cajanus cajan* [L.] Millsp.)	PICS bag	Naturally infested and uninfested grains	6 months	Unchanged	Unchanged		− 6.0%	Mutungi et al. (2014)
	Woven PP bag	Uninfested grains		Δ 2.4-fold	Δ 21.7-fold		− 36.3%	
		Artificially infested grains treated with Actellic Super dust		Δ 3.4-fold	Δ 22.5-fold		− 36.3%	
		Artificially infested grains		Δ 4.2-fold	Δ 43.7-fold		− 49.8%	
Groundnut (*Arachis hypogaea* L.)	PICS bag (Cell A)	Unshelled groundnuts	6.7 months		No weight loss	100% mortality	− 3.1%	Baributsa et al. (2017)
		Shelled groundnuts			No weight loss	Unchanged and remained low	+ 1.1%	
	Woven PP bag (Cell B)	Unshelled groundnuts			Lost 8.2% weight	*T. castaneum* population Δ 2.7-fold; *C. cephalonica* population Δ 6-fold; *Cryptolestes ferrugineus* population Δ 3.2-fold.	− 17.8%	
		Shelled groundnuts			Lost 28.7% weight	*T. castaneum* population Δ 174-fold; *C. cephalonica* population was unchanged	− 73.8%	
Sorghum (*Sorghum bicolor*)	PICS bag	Naturally infested grains	12 months	Δ 1.1-fold	Δ 4.4-fold	Δ 2.8-fold	− 11.6%	Waongo et al. (2019)
	Woven PP bag			Δ 33.7-fold	Δ 53.1-fold	Δ 40.0-fold	− 32.9%	
Rice (*Oryza sativa*)	Single layer SG bag	Naturally infested grains	6 months		Percent weight loss was 0.29%	Unchanged	− 4.1%	Guenha et al. (2014)
	Double layer SG bag				Percent weight loss was 0.27%	∇ 0.7-fold	− 6.4%	
	Woven PP bag				Percent weight loss was 3.0%	Δ 30.6-fold	− 29.9%	
Maize (*Zea mays* L.)	Sealed (hermetic) soda bottle	Artificially infested grains	8 months			No change in insect population	− 15.6%	Williams et al. (2017)
	Unsealed (non-hermetic) soda bottle	Artificially infested grains				Δ7.3-fold	− 32.7%	
Rice (*Oryza sativa* L.)	PICS bag	Naturally infested paddy	18 months	Unchanged	Unchanged	Insect population did not increase		Baoua et al. (2016)
	Woven PP bag			Seed damage increased up to 37-fold	Weight loss increased and reached up to 8.7%	Population of *Tribolium* spp. increased 1.3 to 45.0-fold higher than initial levels; Population of *R. dominica* increased 6–265-fold		

Table 2 (continued)

Commodity	Storage type	Grain conditions	Storage duration	Grain damage	Weight loss	Insect infestation	Seed germination	Reference
Chickpea (*Cicer arietinum* L.)	PICS bag	Naturally infested grains	6 months				− 5.8%	Alemayehu et al. (2020)
	SG bag						− 2.8%	
	Metal bin						− 11.5%	
	Jute bag						− 51.8%	
	Woven PP bag						− 46.0%	
Maize (*Zea mays* L.)	PICS bag (Cell C)	Artificially infested grains	6 months	3.4%	2.0%	2 live adult insects per 125 g	− 22.1%	Njoroge et al. (2014)
		Uninfested grains		0.0%	0.0%	No live adult pests	− 14.3%	
	Woven PP bag (Cell D)	Artificially infested grains		73.9%	47.7%	126.3 adult insects per 125 g	− 86.1%	
		Uninfested grains		50.5%	36.3%	66.7 adult insects per 125 g	− 59.7%	
Maize (*Zea mays* L.)	ZeroFly bag	Naturally infested grains stored in non-hermetic insecticide treated bag	30 weeks	∆ 3.7-fold	∆ 1.7-fold	Live adult insects ∆ 9.4-fold		Abass et al. (2018)
	Woven PP bag	Naturally infested grains		∆ 5.1-fold	∆ 2.5-fold	Live adult insects ∆ 4.1-fold		
	PICS bags	Naturally infested grains		∇ 0.7-fold	No change	Live adult insects ∇ 1.3-fold		
	Metal silo	Naturally infested grains treated with phostoxin fumigant		∇ 0.7-fold	No change	Live adult insects ∇ 1.3-fold		
	Plastic barrel	Naturally infested grains treated with phostoxin fumigant		∇ 0.7-fold	No change	Live adult insects ∇ 11.3-fold		
	Woven PP bag	Naturally infested grains treated with *Shumba* insecticide		∇ 0.7-fold	No change	No live insects at the end of storage		
Rice (*Oryza sativa*)	Woven PP bag	Naturally infested grains	12 months			∆ 3.0-fold		Covele et al. (2020)
	SG bag					∇ 2.3-fold		
	Polyethylene drum					∇ 2.9-fold		
	Polystyrene silo tank					∇ 3.3-fold		
	GrainSafe bag					∇ 3.5-fold		
Hibiscus (*Hibiscus sabdariffa*)	PICS bag	Naturally infested grains	6 months	∆ 1.2-fold	No weight loss	Live adult insect population was less than 2 adults per 500 g	+ 2.3%	Amadou et al. (2016)
	Woven PP bag			∆ 10.7-fold	Lost 8.6% weight	Live adult insect population was 91.2 adults per 500 g	− 31.6%	

∆ means increased; ∇ means decreased; + means increased; - means decreased

Table 2 shows the effectiveness of HS devices in protecting stored grains from insect infestations. From this table, HS controls insect infestation in grains better than traditional storage methods. Despite the protective ability of HS for stored grains, some insect pests such as *R. dominica*, *C. maculatus*, and *P. truncatus* are shown to perforate the HDPE liners of hermetic bags (Chigoverah and Mvumi, 2016; De Groote et al., 2013; García-Lara et al., 2013). This interferes with the airtight seal and compromises the integrity of the hermetic protection.

Effect on Grain Moisture Content, Mold, and Mycotoxin Contamination

The moisture content of stored grains is the most important physical factor in grain deterioration since it favors the growth and proliferation of toxigenic molds (Sawant et al., 2012). When stored under non-hermetic conditions, grains absorb and lose moisture in humid conditions and dryer environments, respectively, until the attainment of equilibrium moisture content (Baoua et al., 2014a; Williams et al., 2014). Apart from exposure to varying external relative humidity levels, grains stored in non-hermetic devices may also gain moisture due to high insect activity and heavy fungal growth resulting from the breakdown of organic matter to yield CO_2, moisture, and heat (Murdock et al., 2012; Njoroge et al., 2014).

HS devices possess an excellent ability to minimize grain moisture changes by (1) functioning as a barrier to moisture migration between the ambient environment and stored grains (Covele et al., 2020; Lane and Woloshuk, 2017; Williams et al., 2017) and (2) limiting moisture production resulting from the aerobic respiration process due to depleted O_2 levels. Due to these, HS storage maintains the moisture content of stored grains at relatively constant levels compared to traditional methods (Aboagye et al., 2017; Baoua et al., 2014b; Chigoverah and Mvumi, 2016; Lane and Woloshuk, 2017; Likhayo et al., 2018; Suleiman et al., 2018; Tubbs et al., 2016; Williams et al., 2014). This is beneficial provided the grain is stored at a safe moisture level (Ng'ang'a et al., 2016b). This characteristic is highly desirable in the tropical and subtropical regions where the ambient relative humidity is always high and grains would gain moisture under no protective action of non-hermetic containers. By maintaining a constant grain moisture content, HS helps prevent the deleterious effects that result from moisture content changes (Ognakossan et al., 2013; Williams et al., 2017).

Yewle et al. (2022) investigated the performance of four different hermetic bag brands (PICS bag, SG bag, and two other brands marketed in India) on stored green gram moisture content during 6 months of storage. The woven PP and jute bags were used as non-hermetic containers for comparison. The average moisture content of green gram increased by about 2% in woven PP and jute bags following 6 months of storage. In all the hermetically stored grains, there was no substantial difference in the moisture content of grains between the onset and after six months of storage.

Mold and mycotoxin contamination in storage is a problem mostly in improperly dried grains (Suleiman et al., 2018), but may also occur due to moisture gain resulting from other factors such as insect activity aside from ambient relative humidity changes. In non-hermetic storage, the high insect population favors mold infestation and hence mycotoxin contamination due to the insect feeding activity as well as the ability to generate localized heat and moisture within the grains (Ng'ang'a et al., 2016b). The growth and accumulation of molds and mycotoxins are low if grains are stored and kept at a moisture content of at most 14% before storage (Magan and Aldred, 2007). Besides proper drying, the O_2 depleted atmosphere characteristic of HS is a constraint to the development of molds and hence mycotoxin accumulation (Tubbs et al., 2016). The low mold growth and mycotoxin contamination in airtight storage are due to the limited biological activity under such conditions. Several studies have demonstrated the effectiveness of HS technologies on mold and mycotoxin contaminations with positive outcomes.

Williams et al. (2014) studied the effectiveness of PICS bags for maize storage on moisture content, mold, and mycotoxin contamination. Maize grains of moisture levels of 12, 15, 18, and 21% and inoculated with *Aspergillus flavus*-infested grains were stored in either PICS bags or woven PP bags at 26 °C for 1 month and 2 months. In woven PP bags, grain moisture content decreased in both storage periods, leveling around 6% after 2 months irrespective of the initial moisture content. In contrast, the moisture content of grains stored in PICS bags remained unchanged at the end of storage. *A. flavus* growth and aflatoxin accumulation were not recorded in any maize stored in PICS bags irrespective of the initial moisture content after 1 or 2 months. In the woven PP bags, low moisture maize (12 and 15%) did not register detectable levels of aflatoxin B_1 but levels of 56.2 ppb and 47.7 ppb occurred in high moisture maize of 18 and 21% moisture content respectively after 2 months of storage.

Ng'ang'a et al. (2016b) compared the performance of PICS bags over the woven PP bags and jute bags for storage of shelled maize under on-farm conditions on aflatoxin contamination during 35 weeks of storage. After 35 weeks, there was a marginal change in mold infestation and aflatoxin contamination in grains stored in PICS bags of at most 14% moisture content. In contrast, mold infestations increased up to 6-fold while total aflatoxin content increased 5–8-fold in woven PP bags and jute bags in the same storage period. While marginal changes in mold and mycotoxin contamination are reported in hermetically stored grains, mold and aflatoxin contamination increased in all the bags with pre-storage moisture content greater than 14%.

In another study, Diarra and Amoah (2019) investigated the effectiveness of storage of maize grains in SG bags on aflatoxin contamination during 3 months of storage. Maize grains pre-infested with *A. flavus* were stored in either SG bags or woven PP bags for 90 days. Total aflatoxin content in SG bags changed marginally and remained below the recommended safe limit of 20 ppb following 90 days of storage. In contrast, total aflatoxin increased profusely in the woven PP bags, exceeding the recommended safe limit at the end of storage.

Despite the protective action of HS on moisture content changes and mold and mycotoxin contaminations, changes in grain moisture content have been reported in some studies. Fusseini et al. (2016) reported an increase in moisture content as well as aflatoxin content in maize grains in PICS bags following storage at different temperatures under laboratory conditions. This study indicated that the largest increase in aflatoxin content occurred at a cooler temperature of 16 °C. Under on-farm storage conditions in Kenya, the number of *Aspergillus* spp. also increased during storage in both hermetic and non-hermetic storage (Maina et al., 2016). The study of mold and mycotoxin contamination may thus not be conclusive due to these conflicting results.

Future Developments and Modifications in Hermetic Storage

The use of HS technologies has become an important consideration in the wake of recognition of the environmental and health implications of fumigants and other synthetic pesticides to control insect pests in stored grains. This is because conventional storage technologies commonly used in developing countries do not adequately protect stored grains without synthetic pesticides. Grain fumigants such as methyl bromide are no longer used in most developed countries unlike in developing countries where they are indiscriminately used due to lack of legislation and regulation. HS is an alternative environmentally friendly technology, and increasing awareness, adoption, and use in SSA are still growing. The authors anticipate the following developments and modifications in the use of HS in the future.

HS technologies are likely to become less costly and more available as manufacturers and distributors become more available and widely distributed in SSA. This would increase technology availability and accessibility to all farming households. One of the major challenges faced by grain farmers is the lack of availability and high cost of hermetic technologies in rural villages and markets. Currently, there are 15 plastic companies globally that manufacture PICS bags, 80% of whom are in SSA and the rest in Asia and Latin America (Baributsa and Ignacio, 2020). Previously, the PICS bag, SG bag, and the metallic silo were the popular marketed forms of a biogenerated HS in SSA. However, the last 10 years or so has seen the manufacture of new HS brands imitating or innovating existing ones. Newer manufacturers are likely to enter the market and this will help improve the overall availability and access of HS technologies.

Furthermore, as cheaper technologies to scavenge O_2 and exude CO_2 become accessible, a shift from a biogenerated modified atmosphere to controlled atmosphere storage is predicted. This would cause rapid depletion of O_2 in a short time without reliance on the biotic components to reduce O_2 levels. In addition, with the growing interest of large-scale users in HS containers such as the hermetic bags and Grain Cocoons, it is anticipated that the use and monitoring of these devices will become automated with time, including processes such as sealing and monitoring grain quality.

Conclusions

Considerable grain quantity and quality storage losses due to insects, molds, and mycotoxin contaminations are still a threat that negatively impact food security, nutrition, and household income of smallholder farmers in SSA. These effects emanate from the interactions between biotic and abiotic factors whose degree determines the magnitude of storage losses. As an improved storage method, HS plays a significant role in smallholder agriculture by significantly reducing storage losses without the need for synthetic insecticides. The use of a biogenerated modified atmosphere HS is currently being promoted and disseminated in many parts of SSA and other regions of the world because of their effectiveness. As seen by this review, HS technology is superior to traditional methods in protecting the integrity of stored grains regarding insect infestation, seed viability, grain damage and weight loss, mold growth, and mycotoxin contamination. The potential benefits realizable from HS use include improved food security, household income, and enhanced international grain trade where quality is highly emphasized. Despite their success in protecting stored grains, their adoption and use have been low in many parts of SSA due to high acquisition costs, lack of knowledge on use and manufacture, and lack of availability in smallholder farming communities where they are needed.

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Declarations

Conflict of Interest The authors declare no conflict of interest.

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