agriculture

MDPI

Review

An Overview of the Post-Harvest Grain Storage Practices of Smallholder Farmers in Developing Countries

Ashish Manandhar [1], Paschal Milindi [1,2] and Ajay Shah [1,*,†]

1 Department of Food, Agricultural and Biological Engineering, The Ohio State University, Wooster, OH, 44691, USA; manandhar.5@osu.edu (A.M.); passmmilindi@gmail.com (P.M.)
2 Department of Agricultural Engineering, College of Agricultural Sciences and Fisheries Technology, University of Dar es Salaam, Dar es Salaam 35091, Tanzania
* Correspondence: shah.971@osu.edu; Tel.: +1-330-263-3858
† Current Address: 110 FABE Building, 1680 Madison Avenue, Wooster, OH, 44691, USA

Received: 2 March 2018; Accepted: 12 April 2018; Published: 15 April 2018

check for updates

Abstract: Grain storage loss is a major contributor to post-harvest losses and is one of the main causes of food insecurity for smallholder farmers in developing countries. Thus, the objective of this review is to assess the conventional and emerging grain storage practices for smallholder farmers in developing countries and highlight their most promising features and drawbacks. Smallholder farmers in developing countries use conventional grain storage structures and handling systems such as woven bags or cribs to store grain. However, they are ineffective against mold and insects already present in the grain before storage. Different chemicals are also mixed with grain to improve grain storability. Hermetic storage systems are effective alternatives for grain storage as they have minimal storage losses without using any chemicals. However, hermetic bags are prone to damage and hermetic metal silos are cost-prohibitive to most smallholder farmers in developing countries. Thus, an ideal grain storage system for smallholder farmers should be hermetically sealable, mechanically durable, and cost-effective compared to the conventional storage options. Such a storage system will help reduce grain storage losses, maintain grain quality and contribute to reducing food insecurity for smallholder farmers in developing countries.

Keywords: food security; post-harvest losses; grain storage; hermetic storage; grain loss

1. Introduction

Globally, more than 500 million smallholder farmers grow crops on less than 10 hectares of land, with most of them located in developing countries [1]. Most of the crop (80%) is produced by smallholders in the largest proportion of cultivated land (80%) in Asia and Sub-Saharan Africa [2]. Rice, wheat, and maize are the most produced and consumed staple cereal crops around the world. Rice and wheat are grown mainly in developing countries in Asia, whereas maize is grown globally in developing countries of Africa, Asia as well as South and Central America [3]. Cowpea is a legume, which is also grown by smallholder farmers mainly in Western Africa, Asia, Central and South America. In most regions in the world, food crops are seasonally produced and continuously consumed throughout the year. However, due to the limited agricultural mechanization available for smallholder farmers in the developing countries, almost all agricultural practices, including pre-harvest and post-harvest operations, such as drying, dehulling, shelling, winnowing and sorting, transportation, and storage, are conducted manually [4]. In such conditions, post-harvest quantitative loss up to 15% in the field, 13–20% during processing, and 15–25% during storage have been estimated [4]. This leads to a huge amount of food loss and decreases food quality, which contributes to food insecurity for the farm household. Annual food spoilage and waste in developing countries is equivalent to about $310 billion, almost 65% of which occurs during the production, processing, and postharvest stages [5]. These losses occur due to financial, managerial, and technical limitations in harvesting, storage, and preservation techniques in developing countries [6]. Thus, improvement in agricultural practices for smallholder farmers is essential to achieve efficient grain supply chain with increased grain yields, reduced grain losses during storage and handling, and reduced time and effort to accomplish harvest and post-harvest operations. Loss during grain storage is one of the main contributors to total post-harvest grain losses [7]. Effective grain storage with minimal grain losses could significantly contribute toward reducing overall food losses for smallholder farmers and have an immediate and significant impact on their livelihoods.

The objective of this review is to evaluate the different post-harvest grain storage practices of the smallholder farmers in developing countries around the world. This review is focused on storage practices applicable to cereal crops such as maize and rice, and legumes such as cowpeas and beans, which are commonly cultivated by smallholder farmers around the globe. The study discusses the different post-harvest losses associated with the grain supply chain. The study also presents the effect of multiple factors, such as insect activities, mold growth and mycotoxins, moisture and temperature, and social factors, on the selection of grain storage systems. Different grain storage practices discussed in this paper are: (1) conventional grain storage structures and handling systems, (2) use of chemicals together with other storage structures, (3) hermetic metal silos, (4) hermetic bagging technology, (5) self-build silos, and (6) on-farm and community-based storage structures. Based on the reviewed storage systems, desirable qualities of storage structure are suggested that could effectively reduce the post-harvest grain storage losses.

2. Post-Harvest Losses of Grain

Post-harvest grain losses include all losses, starting from grain harvesting before it is used for consumption or other purposes. In most developing countries, especially in Sub-Saharan Africa, agricultural productivity is lower compared to developed countries. In addition to the lower agricultural productivity, post-harvest losses of cereals and legumes range from 20–30% in most developing countries around the world [6]. Losses could be in terms or the quantity and quality of grain, both of which significantly reduce the value. Quantitative losses occur due to spillage and scattering of grain, direct infestation by pests, birds and mycotoxins, or mechanical breakages, whereas qualitative losses are mainly due to infestation by mold, mycotoxins, and mechanical breakages. There are different factors associated with different forms and extents of post-harvest losses along the grain supply chain (Figure 1).

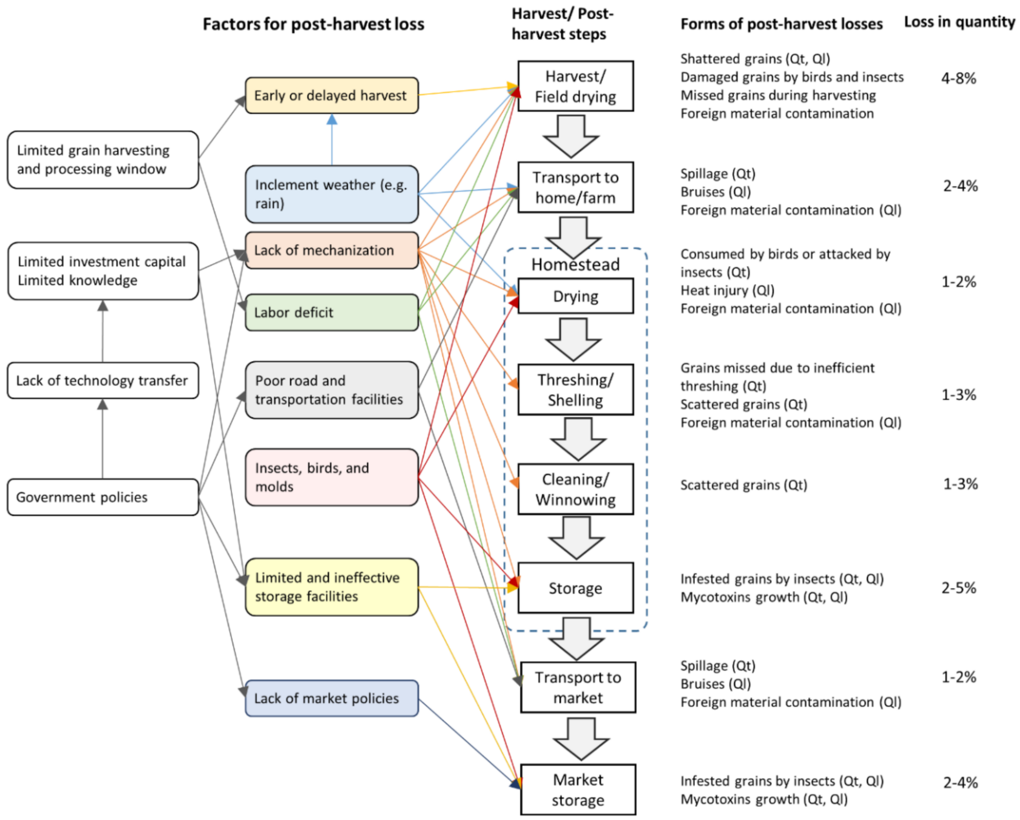

Figure 1. Factors for losses during different post-harvest steps of the grain supply chain in developing countries [7–9]. Note: quantitative grain losses for harvest and different post-harvest steps provided in this figure are based on information provided in African post-harvest information system (APHLIS) [9]. However, grain storage losses up to 34% have been reported by different studies [4,10–12]. Qt—Quantitative loss, Ql—Qualitative loss.

Cereals and legumes are usually harvested within a short harvest period. Harvesting is usually performed manually using a sickle or knife by smallholder farmers. Harvesting needs to be performed at the proper time, possibly just after the crops are mature with grain moisture contents between 20–28% for maize and rice, and 14–18% for cowpeas, to minimize harvesting losses [13,14]. Crops have a higher moisture content when harvested too early, which either will require longer drying times or could provide favorable growing conditions for mold, resulting in increased costs or losses. Also, if harvesting is done during rain, the increased grain moisture content could result in unexpected grain germination. If the crops are harvested too late, they are exposed longer in the field and have more chance of being attacked by birds, insects, and mold. Furthermore, field drying of the grain could result in losses due to shattering of grain during harvesting.

Smallholder farmers transport the harvested grain to the homestead by carrying them, or using bicycle or bullock carts. Some farmers hire trucks to haul their grains. Losses due to grain spillage and bruises can occur during transportation. Foreign materials could also contaminate the grains if not properly secured during transportation. Grain is usually field-dried or naturally dried in mats or cribs in a homestead yard with potential losses during drying by infestation from birds or insects, or heat injury. Depending on the regions, the grain is then stored with either cobs or stalks intact in cribs or threshed/shelled, cleaned, and stored in different storage structures. Some farmers de-husk and shell the grain in the field, while others do it in their homes. Grain is normally stored in jute bags, propylene sacks, or traditional cribs for a few months (based on personal communication with farmers in rural Tanzania but applicable to most developing countries). In some cases, maize is stored for almost seven months until the next harvest is available. The market price also tends to increase within six months of storage [4]. Storage losses, mainly occurring due to insects and mycotoxins, are considered to be the highest among the post-harvest steps of grain produced by smallholder farmers and could occur in farm as well as market storage. Different storage practices are discussed in further detail later on. Most of the grain is stored to be consumed by family members, whereas some grain is usually stored for a few months and then sold to the market depending on the grain quality after storage [1]. The grain is then transported to the market where it might be stored further before being purchased and used by other people.

3. Factors Affecting Grain Storage Practices

Grain is usually stored for several months after harvest, which is much longer than other grain post-harvest steps [11]. Also, the grain is minimally monitored during storage. Thus, proper grain storage conditions are needed to minimize grain losses. Factors that play a crucial role in storage losses can be classified as physical, biological, and socioeconomic.

3.1. Physical Factors—Temperature, Moisture, and Oxygen

Physical factors such as oxygen, moisture, relative humidity, and temperature have a major impact on the storability of grain. Physical factors influence the conditions for insect multiplication and mold growth during grain storage, which eventually affects the storability of the grain.

Temperatures in the range of 25 to 35 °C create favorable conditions for the rapid growth of most storage insects [15]. Under these conditions, insect reproduction accelerates, which increases grain consumption and generates more heat, maintaining an optimal environment for insects. However, at temperatures lower than 13 °C or higher than 40 °C, insects tend to lower their activity, migrate, or eventually die [16,17]. Also, mold growth was observed in storage conditions with a temperature between 20 °C and 40 °C, with optimal growth for the majority of molds occurring between 25 °C and 30 °C [18]. At the appropriate temperature and moisture content and with the availability of food sources (grain in this case), mold spores settle on a surface and grow rapidly. In addition, temperature gradients also promote moisture collection at specific locations in the storage system, which provides favorable conditions for mold growth [19]. When cereals are stored in a silo or warehouse, the temperature at the center of the grain volume remains relatively similar to that during harvest, and the grain farthest from the center that is in contact with the storage walls has temperature variations based on the ambient air temperatures. Thus, for grain stored at a high moisture content and high relative humidity, when the outside temperature decreases, the walls cool faster, which causes condensation and develops wet spots, facilitating mold growth.

Mold and insects require moisture for their growth. Mold proliferates at a relative humidity (RH) above 70% [18], and thus grain needs to be stored at lower RH, preferably below 60%, especially if stored for extended periods. The equilibrium moisture content corresponding to this RH for most cereals is below 13% and for legumes/beans is below 15%, which is preferable for long-term grain storage [20]. Higher moisture content has shown to be detrimental to grain in terms of dry matter loss and quality [21]. Lowering the RH to 9% during storage has been shown to increase insect mortality up to 98% within 24 hours [22]. Furthermore, available water is used by insects as it is one of the main requirements for their survival. In one study, 100% of weevils in stored grain were dead in six days for grain stored in hermetic conditions without access to oxygen and external water, whereas 5% and 28% of the insects were dead in grain stored at 16% and 6.3% moisture contents, respectively [23].

Higher moisture and oxygen availability increases the grain respiration rate and generates heat, carbon dioxide, and enzymes, which break down the starch, proteins, and lipids in grain. Insects utilize the available oxygen during metabolic activities and raise the carbon dioxide concentrations within the hermetic storage system through respiration. The insects' feeding activity drops progressively in proportion to the varying gas concentrations and nearly stops at 3–6% (v/v) oxygen and 15–18% (v/v) carbon dioxide [24]. However, for near-complete control and to achieve almost 100% insect mortality, the O_2 concentration should drop to 1–3% or CO_2 should rise to 35% [25,26].

3.2. Biological Factors—Insect and Rodent Activity, and Mold Growth during Grain Storage

3.2.1. Insect/Pest and Rodent Activity

Insects/pests and rodents are the major factors affecting grain quality and grain losses in developing countries [27,28]. In research involving stored maize in Tanzania, around 18% of the shelled maize was found to have weevil damage [29]. Geography and climatic conditions affect the probability and severity of grain infestation by insects and pests [30–32]. Pest infestations can occur in the field as well as during storage (Table 1) [33,34]. In most storage practices, insect growth and mold formation take place within the system. However, depending upon the storage types and conditions, their active period differs.

Different insects that infest grain at different phases of growth, storage, and processing are summarized in Table 1. Insects mainly damage the stored products by direct feeding. These insects feed on the endosperm, resulting in a loss of weight and quality of grain as well as grain germ, causing poor seed germination [35]. Grain infested by insects loses value for consumption or planting. Grain borers, such as the large grain borer (LGB) (*Prostephanus truncatus*), and grain weevils (*Sitophilus granarius*), are the main pests responsible for grain storage losses [4,36]. The maize weevil (*Sitophilus zeamais*) is the main insect responsible for the deterioration of stored maize, sorghum, and other grain in the tropics [37,38]. As these attack intact grain, they are also labeled as primary pests, whereas secondary pests such as the red flour beetle (*Tribolium castaneum*) attack already infested grain. Birds and rodents can infest the grain while in the field before harvesting, whereas rodents could also be a problem during storage.

Table 1. Common insects and rodents infesting grain in developing countries [34,39,40].

Insects and Rodents		Commodities Infested	Status Level			
			Pre-Harvest	Unshelled	Shelled	Milled Kernels
Beetles	*Sitophilus zeamais* (Maize weevil)	Maize, sorghum and rice	2	3	5	4
	Sitophilus oryzae (Rice weevil)	Wheat, sorghum and rice	1	3	5	4
	Acanthoscelides obtectus	Beans	3	3	5	3
	Prostephanus truncatus (Large Grain borer)	Maize	2	5	3	1
	Rhyzopertha dominica	All cereals	-	2	4	2
	Tribolium castaneum & other secondary beetles	All cereals	1	1	2	3
	Lasioderma serricorne	All cereals	-	-	1	1
Moths	*Sitotroga cerealella* (Angoumois Grain moth)	All cereals	2	4	3	2
	Ephestia cautella & other warehouse moths	All cereals	-	1	3	3
Rodents	Rats and mice	All cereals	4	3	2	1

Note: Status levels—refers to prevalence and potential damage from insects and pests (adapted from reference [40]: 1—very low (possibly negligible), 2—low, 3—low to moderate, 4—moderate to high, 5—high.

3.2.2. Mold Formation and Growth

Mold formation in stored grain can produce different mycotoxins, which are toxic chemicals unsuitable for human consumption. In addition, mold generates other problems besides mycotoxins, such as dry matter loss, odor, and a loss of nutritional value. Thus, the presence of active mold in stored grain can greatly limit grain usage due to quality loss and mycotoxin formation. Mycotoxins, such as aflatoxins, ochratoxins, trichothecenes, zearalenone, and fumonisins, developed mainly from fungi, such as *Fusarium*, *Aspergillus*, and *Penicillium*, are common in grain in most countries (Table 2) [41]. Mold can develop on the crop in the field as field fungi, as well as during storage as storage fungi, thus creating two bases of mycotoxins owing to mold formation. Mold growth during grain storage is dependent on grain moisture content, temperature, gas composition, relative humidity (RH), and fungus contamination during field harvest and storage [42,43]. Reducing the grain moisture content to less than 13% and relative humidity to less than 60% during storage is crucial to limit mold activity [44]. Field-based fungi require a much higher moisture content and thus rarely develop under storage conditions because of limited moisture and water activity [42]. However, storage fungi such as *Aspergillus* sp., which produces aflatoxins, could develop well at RH between 70% and 90% [45], which corresponds to an equilibrium moisture content higher than 16% for most grain [20]. Thus, mold formation needs to be properly addressed during storage to minimize grain losses.

Table 2. Different mycotoxins affecting maize quality [44,46–48].

Mycotoxin	Fungal Source	Contamination Location	Effects
Aflatoxin (B1, B2, G1, G2)	*Aspergillus flavus, Aspergillus parasiticus*	Field and storage	Potent human carcinogen and increased susceptibility to disease. Adverse effects in animals, especially chickens.
Fumonisin B1	*Fusarium moniliforme*	Field and storage	Suspected human carcinogen. Toxic to pigs, poultry and horses.
Ochratoxin A	*Aspergillus ochraceus, Aspergillus carbonarius, Penicillium verrucosum*	Storage, occasionally from field	Suspected human carcinogen. Shown to be carcinogenic in laboratory animals and pigs.
Zearalenone	*Fusarium graminearum, Fusarium culmorum, Fusarium crookwellense*	Field and storage	Possible human carcinogen. Affects reproductive system in female pigs.
Deoxynivalenol/nivalenol	*Fusarium graminearum, Fusarium culmorum, Fusarium crookwellense*	Field	Toxic to humans and animals, especially pigs.
Trichothecenes	*Fusarium graminearum, Fusarium culmorum*	Storage	Intestinal irritation leading to feed refusal in livestock.

3.3. Socioeconomic Factors

The adoption of different storage structures also depends on socioeconomic factors, such as the farmers' family size, land holding size, required grain storage duration, off-farm income, road accessibility, market price of grain, and grain safety during storage [49]. Usually large families have a greater demand for grain consumption and, thus, could more readily adopt better grain storage practices. Smallholder farmers with a relatively larger land holding could afford new storage technologies compared to those with a small farm area. Farmers having off-farm income have more financial resources at their disposal to invest in effective storage technologies. Farmers requiring grain to be stored for a longer duration for a higher selling price usually prefer improved storage technologies for grain storage compared to those storing for a shorter time. The higher market price of the good-quality grain after a few months of storage provides justification for farmers to spend more to store their grain for minimal loss or to preserve quantity and quality. Farmers preferring security of their grain from potential theft or effects of adverse climatic conditions tend to store their grain in portable containers inside their houses. As an example, many households in Kenya prefer to shell and store maize in their houses due to lower maize production and increased incidences of theft [39]. Also, farmers open to new technologies are more likely to implement newer grain storage practices.

4. Grain Storage Practices in Developing Countries

Grain produced by smallholder farmers is stored for a few months to a year before being consumed or sold at market. The grain needs to be protected from unfavorable conditions and pests during storage. This is usually accomplished to a certain extent by storing them in structures made from different materials or by mixing them with natural or chemical products. Farmers incur different level of grain losses depending on their storage practices. Findings from some recent studies [10,50,51] are summarized in Table 3. These studies have evaluated the efficacy of different storage practices based on different factors, such as % grain losses (wt % of grain reduced), % grain damaged (% of grain damaged during storage, determined by visual observations), number of holes in 100 grain seeds (determined by visual observations), and comparative weight of 100 grain seeds (Table 3). The variations in the results for similar storage structures could be due to differences in the locations, initial condition of the stored grain (insects and pests already in the grain), storage conditions, and storage duration.

Table 3. Effectiveness of different grain storage practices of smallholder farmers in developing countries.

Study	Storage Technology	Storage Duration (Months)	Grain Weight Loss [1] (%)	Grain Damage [2] (%)	Number of Holes in 100 Grain Seeds	Weight of 100 Grain Seeds (g)	Total Mold Counts ($\times 10^3$ cfu/g Grain)
De Groote, 2013 [10] Study on maize performed in Kenya	Propylene bag	6	24 ± 9.8	80	-	-	-
	Propylene bag + Actellic Super	6	8.2 ± 4.1	18	-	-	-
	Super Grain bags	6	6.3 ± 1.9	13	-	-	-
	Metal silos	6	1.4 ± 0.4	8	-	-	-
	Metal silos + Actellic Super	6	1.2 ± 1.1	1	-	-	-
	Metal silos + Phostoxin	6	0.7 ± 0.6	1	-	-	-
Wambugu, 2009 [50] Study on maize performed in Western Kenya	Stored above fireplace	6	-	54.5	-	-	-
	Gunny bag + Cow dung ash	6	-	46.9	-	-	-
	Plastic container+ ash	6	-	0.9	-	-	-
Ndegwa, 2016 [51] Study on maize performed in Kenya	Polypropylene bags	4	2.4	17.5	-	-	-
	Polypropylene bags + insecticide	4	1.3	14	-	-	-
	SuperGrainBag™	4	0.3	3	-	-	-
	SuperGrainBag™ + insecticide	4	1.2	4	-	-	-
Baoua, 2012 [52] Study on cowpea performed in Niger. 500 g of grain were stored for each treatment condition. 100 seeds were sampled for comparison	Linen bags (control)	5	-	-	329.8 ± 71.2	6.6 ± 0.7	-
	B. senegalensis	5	-	-	331.3 ± 51.5	5.3 ± 1.0	-
	Sand	5	-	-	74.7 ± 16.3	13.3 ± 0.6	-
	Ash	5	-	-	77.7 ± 20.1	13.2 ± 0.6	-
	Triple bag	5	-	-	59.8 ± 12.1	12.7 ± 0.6	-
	Solar	5	-	-	48.2 ± 11.8	13.2 ± 0.6	-
	Phostoxin	5	-	-	40.6 ± 8.6	13.6 ± 0.6	-
Baoua, 2013 [53] Study on cowpea in Niger	Initial infestation	4	-	-	21.6 ± 0.7	14.9 ± 0.1	-
	PICS bags	4	-	-	18.5 ± 0.7	15.2 ± 0.2	-
	SuperGrainBag	4	-	-	21.9 ± 1.1	15.2 ± 0.1	-
	Woven bag	4	-	-	227.6 ± 17.5	9.7 ± 0.1	-
Chigoverah, 2016 [11] Study on maize performed in Zimbabwe	Untreated control	10	<27	>80	-	-	-
	Metal silo	10	<7	<25	-	-	-
	SuperGrainBag	10	<12	<25	-	-	-
	Synthetic pesticide	10	>34	>75	-	-	-
Nganga et al., 2016 [12]	Jute bags at mc < 13%	9	-	-	-	-	115.6

Table 3. *Cont.*

Study	Storage Technology	Storage Duration (Months)	Grain Weight Loss [1] (%)	Grain Damage [2] (%)	Number of Holes in 100 Grain Seeds	Weight of 100 Grain Seeds (g)	Total Mold Counts ($\times 10^3$ cfu/g Grain)
Study on maize performed in Kenya	Polypropylene bags at mc < 13%	9	-	-	-	-	126.3
	PICS bag at mc < 13%	9	-	-	-	-	21.6
	Jute bags at mc > 14%	9	-	-	-	-	215.7
	Polypropylene bags at mc > 14%	9	-	-	-	-	201.4
	PICS bag at mc > 14%	9	-	-	-	-	160.3
Quezada et al., 2006 [41] Study on maize performed in Mexico	Nonhermetic at mc = 14%	0.5	-	2	-	-	-
	Hermetic at mc = 14%	0.5	-	1	-	-	-
	Nonhermetic at mc = 17%	0.5	-	94	-	-	-
	Hermetic at mc = 17%	0.5	-	1	-	-	-
Freitas et al., 2016 [54] Study on beans storage in Brazil	Non-hermetic glass bottles mc = 15%	4	-	54	-	-	-
	Hermetic silo bags	4	-	<5	-	-	-
	Hermetic plastic bottles	4	-	<5	-	-	-
Mlambo et al., 2017 [55] Study on maize storage in Zimbabwe	Untreated	4	1.09	-	-	-	-
	Shumba super dust	4	0.21	-	-	-	-
	Actellic gold dust	4	0.16	-	-	-	-
	Metal silo	4	0.14	-	-	-	-
	PICS bag	4	0.01	-	-	-	-
	SuperGrainBag	4	0.37	-	-	-	-
	Aloe ash	4	0.20	-	-	-	-
	Untreated	6	1.82	-	-	-	-
	Shumba super dust	6	0.92	-	-	-	-
	Actellic gold dust	6	0.03	-	-	-	-
	Metal silo	6	0.28	-	-	-	-
	PICS bag	6	0.04	-	-	-	-
	SuperGrainBag	6	0.34	-	-	-	-
	Aloe ash	6	1.94	-	-	-	-

Note: Parameters with '-' were not estimated or reported in the cited study. [1] % grain weight losses—% weight of grain reduced, [2] % grain damaged—% of grain damaged due to physical spoilage or deterioration such as holes, cracks, and discoloration. mc — moisture content.

4.1. Conventional Storage Structures and Grain Handling Systems

Conventional storage systems were predominantly used in the past and are still used in societies that prefer to store grain traditionally. For example, about 60–70% of food grain produced in India is estimated to be stored in conventional storage structures and grain handling systems [56]. Conventionally, grain is stored either after being shelled (such as for rice and beans) or intact with cobs (as in maize for some regions of the world). Conventional storage structures are usually built by smallholder farmers using locally available resources, such as mud, wood, wheat and paddy straw, bamboo, cow dung, and bricks [56,57].

Traditional on-farm and domestic storage systems include fireplaces, local cribs, roofs, woven granaries, structures/bins constructed with wire mesh or steel net, underground pits, and wooden platforms [8,57]. These types of storage structure are suited for maize grain stored intact with cobs in ears, and are very common around the world. Maize is stored over the fireplace on top of rafters by many farmers in Asia and rural Mexico to reduce grain moisture and prevent attack from insects [58,59]. Grain storage bins made of steel net and wire mesh are also common maize storage options for smallholder farmers in China and Central America [60,61]. The steel net or wire mesh is wrapped around bamboo or wooden pole structures for storage. The storage unit is covered on the top with biomass or corrugated metal sheets. Woven granaries constructed from bamboo and straws are also used to store shelled or intact grain by farmers in developing countries in Asia, Africa, and Latin America [58,59]. Underground grain storage pits, used around the world for centuries, are fired in situ and layered with straw or woven bamboo [62]. Most of these conventional storage structures are constructed in the homestead and provide protection against rain and sun. Traditional storage structures that are widely used for storing grain in the Indian subcontinent include kanaja (a structure made from bamboo and plastered with mud and cow dung), kothi (a specially constructed room), sanduka (wooden boxes to store up to a few hundred kilograms of grain and pulses), utrani (burnt earthen clay pots for storing small quantities), and hagevu (an underground dugout pit lined with locally available materials such as stones or straws) [56,59,63]. Mud bins or earthen clay pots plastered with cement or coated with a layer of bitumen to improve the grain storage conditions are also being used [59]. Furthermore, polyethylene layers sandwiched between mud layers of a grain storage bin have also been used in Nepal [59].

Space is a major challenge with conventional storage systems. For instance, granaries occupy a large space indoors. For outdoor storage, cribs and underground pits occupy a large space. Also, the construction skills for conventional storage structures, such as woven granaries, underground pits and cribs are disappearing from the local communities. At times, traditional storage boxes, such as sanduka, could be costlier to build for smallholder farmers.

Other popular grain handling and storage systems that can be used for both shelled and intact grain include synthetic polypropylene bags and gunny sacks [50]. Polypropylene and sisal bags with storage capacities ranging from 25 to 100 kg are used for all types of storage and are popular globally [64]. Plastic tarp layers are also used extensively as cover for stored bags and other storage structures to prevent them from rain. The use of bags/sacks to store cereals has increased because they occupy less space when filled with grain, and even smaller space when empty. Also, they are portable and readily available in rural markets, and thus grain can be stored, transported to the market, and sold or traded as needed [8].

Conventional storage structures contain the grain, prevent spillage, provide protection against rodents, insects, and pests that might come in contact with grain during storage, and keep it safe from outside elements such as rain and sun. However, air and moisture present in the ambient air can pass through most of these structures and thus are not effective against insects, pests, and mold that are already present in the grain during harvest and are stored together with the grain. To improve effectiveness, most of the smallholder farmers using conventional storage technologies mix the grain with some natural preservatives, such as ashes, leafs, oils from different plants, or chemicals to prevent early degradation [63,65].

4.2. Use of Chemicals and Pest Repellents

Grain can be protected from insects, pests, rodents, and mold to some extent using different additives and chemicals together with conventional storage systems. These additives and chemicals are effective at creating a toxic storage environment, lowering the pH, or leaving an unpleasant smell. Smallholder farmers have traditionally stored grain using locally available plant leaves, oil, and ashes, which can be considered biopesticides. Dried walnut leaves, cow dung ash, turmeric or onion rhizomes, mint leaves, neem leaves, eucalyptus, lime, and mustard oil are some of the traditional grain preservatives used in the Indian sub-continent and Sub-Saharan Africa [29,56,66]. Cowpeas are often mixed with sieved ashes from cooking fires to limit weevil activity [65]. Some farmers practice traditional pest control by mixing grain with herbs, such as Mexican marigold and hot pepper [67]. Different botanical pesticides have been used throughout the world and are found to be effective as grain protectants [68].

In addition to traditional storage practices that use locally available natural materials, the use of synthetic chemicals, such as phosphine, actellic super, shumba dust, and super grain dust is also common in developing countries (Table 4). These chemicals must be applied at predetermined rates and thoroughly mixed with properly dried grain to obtain the desired effects [34]. Phosphine (commercially known as Phostoxin®) and methyl bromide are applied as fumigants for grain stored in mud sealed or cemented granaries, metal bins, and silos [69]. Grain borers, such as *P. truncatus*, can be controlled quite easily with fumigants such as phosphine, in dry grain with less than 13% moisture content [70]. However, only licensed technicians are authorized to handle phosphine in many countries. In China, state depots for grain storage commonly use phosphine fumigation to prevent insects, although it is not acceptable for farmers with storage in the house [60,71]. Other insecticides, such as actellic super, shumba dust, super grain dust, and diatomaceous earth, are readily available in the market and can be directly used by farmers (based on personal communication with smallholder farmers in Tanzania, and [34]). Pesticides provide an alternative method of grain preservation in areas with limited access to effective grain storage systems, and to energy and equipment for drying and maintaining grain at safe moisture levels. Pesticides can effectively control pest and insect infestations and prevent grain losses; however, their effectiveness can be reduced over time, after which the grain is susceptible to losses [55].

Table 4. Insecticides used during grain storage in developing countries [34,72,73].

Insecticide Common Name	Chemicals Used	Application Rate	Comments
Actellic Super	Pirimiphos methyl and Permethrin	50 to 100 g in 90 kg	LGB, maize weevils
Shumba dust	Deltamethrin and Fenitrothion	50 g in 90 kg	LGB, maize weevils
Super grain dust	Bifenthrin	100 g in 90 kg	LGB, maize weevils
Phostoxin or Phosphine	Aluminum phosphite	6 tablets for 1 ton of maize under tarp	LGB Fumigant Very toxic Require trained applicators No residual protection
Diatomaceous earth	Silica	250 g in 90 kg maize	Weevil, beetle, moth Low grain moisture and RH preferred
NeemPro	Neem	6 g per kg of maize	Maize weevils

An increased use of these chemicals has, however, resulted in resistance among targeted species and, thus, reduced their effectiveness [74,75]. In addition, adulteration of these pesticides within the supply chain, associated environmental and health-related concerns due to unwanted pesticide exposure to smallholder farmers, and higher costs for marketing new chemical pesticides have limited the emergence of new chemicals effective for grain storage [74,76–78].

4.3. Non-Hermetic Storage

Non-hermetic storage systems are common in most developing countries. In most cases, these storage systems provide safety against attack from insects, pests, and rodents and from rain and sun. They also protect the grain from being stolen when stored inside houses or warehouses. However, they do not provide any barrier for air during storage and thus, are not effective against insects, pests, and mold already present in the grain. Different chemicals can be used in conjunction with these storage structures to preserve the grain against the insects, pests, and mold already present in the grain. Non-hermetic storage systems are usually comprised of household-scale self-build silos and community-scale storage structures and warehouses.

4.3.1. Self-Build Silos

The self-build silo is made of corrugated galvanized iron (commonly used as a roofing material) or HDPE sheets sandwiched between earthen walls, which act as an insulation between the stored grain and the surrounding environment. These storage structures are being promoted in rural African villages and have been widely adopted in rural India (commonly known as Pusa bins) for smallholder farmers [56,79,80]. These silos usually have capacities between 1 and 2 cubic meters. The cost of constructing a self-build silo is relatively low. Material costs are low because of their local availability. In addition, advanced technologies are not required to construct these silos so smallholder farmers can easily fabricate them in rural villages. The corrugated galvanized iron sheet used as a roofing material for rural houses is normally used to make metal bins or silos. The cost of earthen walls for insulating the silos only includes the cost of labor [79].

4.3.2. On-Farm Storage and Community Storage Structures

On-farm storage structures provide farmers with maximum flexibility and the ability to maintain control on their farmstead. The storage bins are usually tower silo bins with a much higher capacity than self-build silos, and the grain is usually dried to safe moisture levels before storage. The storage system protects the grain from weather elements, insects, pests, and mold when stored at safe moisture levels. Fumigants and preservation chemicals can be used with these storage systems to further protect the grain. However, it is a challenge for rural smallholder farmers to invest in large-scale on-farm storage structures unless they unite in groups since they requires a large investment of capital [81]. The condominium storage space is an option that is provided by a commercial elevator, which manages the storage and guarantees the grain quality throughout the storage period. The technologies associated with these storage systems require higher technical skills and capital investment, which makes it infeasible for a smallholder farmer in developing countries [81]. On-farm storage structures and condominium storage structures could be feasible for rural smallholder farmers in developing countries if they are purposely made for a group or cooperative of smallholder farmers.

4.3.3. Warehouses

Community- or government-run storage, such as warehouses or cover and plinth (CAP) structures, are also common grain storage options for smallholder farmers in developing countries [56]. These are housed storage spaces that protect the grain from the elements. Smallholder farmers can store certain types of grain including maize, typically using bags for effective record-keeping, in these systems, paying a specified fee [82]. CAP storage refers to the storage of stacks of bagged grain on top of wooden pallets, with waterproof low-density polyethylene sheets or tarps covering the top and all four sides [82]. Food grain is stored in CAP storage for six to 12 months. The CAP storage system in India was originally promoted as a necessity rather than a better storage option because harvest volumes were higher than the available warehouse storage space [83]. Although these storage systems allow for large-scale grain storage, protect the grain from the elements, and are economical, they are not effective in terms of grain protection from rodents, insects, pests, and mold. For insect and pest control in such a storage system, pesticides such as malathion and deltamethrin and fumigants such as phosphine are used. For rodent control, poison baits are commonly used [56].

4.4. Hermetic Metal Silos

Hermetic metal silos (Figure 2), which are airtight storage structures constructed from a galvanized metal sheet, have been promoted in recent years in most developing countries in Central America, Africa, and Asia as an alternative to chemical use during grain storage [56,60,84–86]. They are commonly known as Punjab Agricultural University (PAU) bins in the Indian subcontinent [56]. In the sealed hermetic storage structure, respiration of living organisms depletes oxygen and produces carbon dioxide, creating an environment that kills insects and pests in the stored grain [87,88]. It also acts as a barrier for moisture exchange between the environment inside and outside the storage structure, thus limiting mold formation [11,88,89]. In addition to this, metal silos are also effective against rodents, birds, and insects [84,90]. The reduction in mold and pests contribute to better grain storage conditions and lower grain losses.

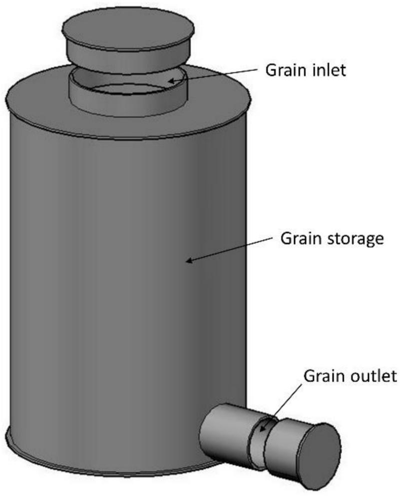

Figure 2. Metal silos used for grain storage in developing countries.

Many research studies [10,11,49,84,91] have compared metal silos with conventional storage structures and chemicals used for grain storage and concluded that metal silos are the most effective. However, for cereals to be stored safely in a metal silo, the grain must be dried to a moisture content of less than 14% to limit mold formation [84]. A propensity score has also been used to assess the impact of silo structure on maize storage duration, storage losses, and costs [49]. A survey of farmers found that smallholder farmers who adopted the silos lost an average of only 3 kg, worth $2, and were able to store the grain for 1.8 to 2.4 months longer compared to an average loss of 157 to 198 kg of grain, worth $104–132, for non-adopters.

Although metal silos substantially reduce insect and pest infestation and potentially improve smallholder farmers' food security and income, their high initial production cost compared to the other storage structures, the limited availability of galvanized iron sheets in rural markets, and few local metal silo manufacturers limit its widespread adoption by smallholder farmers in developing countries [10,49,51]. The main production cost elements of metal silos are a galvanized iron sheet, labor, and transportation. The initial cost of building the most common metal silos of 1 ton (the smallest size considered to be cost-effective) and 1.8 ton capacities are $173 and 193 (cost adjusted for 2017), respectively, which is very high for smallholder farmers [49,92]. Tefera (2011) reported the production and distribution costs of metal silos in Kenya in 2008–2009 to be in the range of $29 (cost adjusted for 2017) for 90 kg capacity to $243 (cost adjusted for 2017) for 1800 kg capacity. In general, to be cost-effective, it is recommended that the seeds for planting in subsequent years should be stored in a small metal silo of 100–200 kg capacity, while those for consumption should be stored in a larger metal silo of 300–3000 kg capacity [84]. Different sizes of metal silos have been promoted to the rural smallholder farmers in Central America and Africa by providing a financial subsidy or credit, which is crucial for the adoption. The favorable capacities of metal silos are 550 kg and 820 kg for most families in developing countries, which corresponds to the annual grain consumption of an average family of 5–6 members [84,93,94]. In addition, failure to maintain a hermetic seal during storage could significantly reduce the effectiveness of storage. Determination of oxygen and carbon dioxide levels inside the storage structures and pressure decay tests could be helpful in determining the hermeticity and effectiveness of these storage structures [95,96].

4.5. Hermetic Bagging Technology

Hermetic bagging technology uses one or two layers of high-density polyethylene (HDPE) bags together with another layer of polypropylene or conventional bags to store the grain. Two types of hermetic bags, namely Purdue Improved Crop Storage (PICS) bags and SuperGrainBag™, have commonly been used by smallholder farmers in developing countries in recent years. PICS bags use a triple-bagging hermetic storage technology (Figure 3), and are used extensively in Africa and Latin America [97]. A PICS bag consists of two inner layers of HDPE bags of 80-micron thickness, which limit the oxygen permeability, and a third outer layer that is a woven polypropylene bag. This layer acts as a casing for the two inner polyethylene bags and ensures the mechanical strength of the storage bag as a whole [98,99]. SuperGrainBag developed by Grain Pro Inc. consist of an HDPE inner lining with an oxygen barrier, which creates the hermetic conditions, and a protective propylene bag. These are often sold only with the inner liner bag, with farmers using their own bags for outer protection [51]. Bags with capacities between 25 kg and 100 kg are available at prices ranging from $3 to $5.3 for 90 kg bags and with a useful life of two to four years [39,51].

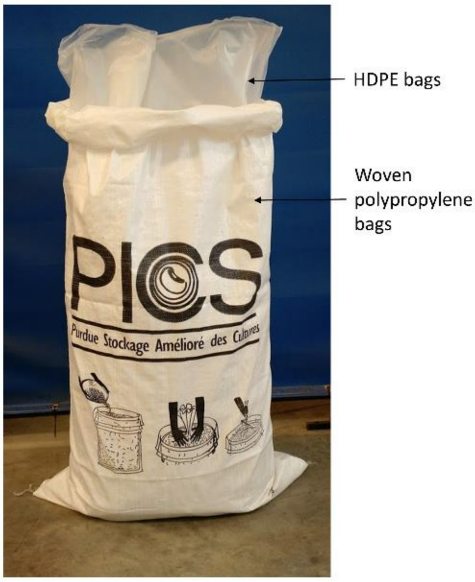

Figure 3. Triple-bagging hermetic storage for developing countries.

Both PICS bag and SuperGrainBag were found to be effective at controlling pests and limiting grain loss compared to conventional woven plastic bags under similar storage conditions (Table 3) [53]. Conventional woven bags were compared with both new and reused PICS bags for storing cowpeas for five months under normal conditions in Niger. The results showed that both new and used PICS bags were effective at controlling insect and pest infestations in cowpeas, and had 40% more grain weight (12.6 to 13.9 g) per 100 cowpea grain when compared to the conventional woven bags (7.6 g to 8.2 g) [100]. Both PICS and SuperGrainBag have been widely adopted in West and Central Africa due to their effectiveness, simplicity, low cost, small storage space requirement, durability, ease of production, and local manufacture [51,99,100]. Silo bags and plastic containers were also used as hermetic grain storage, which showed reduced grain infestation compared to the control, in which grain was stored in non-hermetic conditions [54]. Some of the major disadvantages of the hermetic bags, when compared to other improved systems, are that they are highly susceptible to physical damage, such as puncture from sharp protruding objects, as well as abrasions and perforations from insects and rodents [10,53,101]. Additionally, they can burst during transportation from one location to another, especially when the bags are large. Punctures and physical damage reduce the useful life of the bags, and thus add to the cost of this system.

5. Comparison of Different Grain Storage Practices of Smallholder Farmers in Developing Countries

Different grain storage technologies are available to smallholder farmers; each has different pros and cons, as briefly summarized in Table 5. Traditional storage options such as granary and polypropylene sacks are socially accepted, convenient, require minimal investment for smallholder farmers, and prevent the grain from being attacked by external insects, pests, and rodents. However, they allow air and moisture to pass through the grain; thus, insects, pests, and mold already present in the grain may grow and infest the grain during storage. Using chemicals could be effective at killing insects already present in the grain. However, they are expensive and may be potentially be toxic to humans, which may make them socially unacceptable to farmers. In addition, for grain stored for a longer duration, the efficacy of pesticides and preservatives in preserving the grain could significantly reduce over time. Chemicals should be properly monitored during application to be effective against pests and mold. They also need to be reapplied periodically. Adulteration of chemicals and limited awareness to farmers on proper chemical use could create health hazards and reduce their effectiveness for grain storage.

Hermetic storage technology limits the movement of air and moisture from the external environment to the stored grain, which results in reduced oxygen and moisture conditions inside the storage system. This creates an unfavorable condition for the survival and growth of insects, pests, and mold, providing an effective control. In addition, hermetic bagging technology is easy to use, involves low costs, and is readily available for smallholder farmers. However, the durability of these bags is a major concern, as they are vulnerable to punctures from sharp objects, grain, insects, and rodents while transporting or storing the grain. Punctures in the bag can sometimes be sealed by grain, but there are also chances for the air to enter the storage bag, significantly reducing its effectiveness for grain storage. Self-build silos are more durable compared to hermetic bagging technology as they are fabricated from layers of metal or plastic sheets covered with grass and clay. However, the self-build silo is permanent and is usually constructed for outdoor use. It cannot be moved from one place to another. Hermetic metal silos also effectively maintain hermeticity and grain stored in them has relatively lower losses compared to other conventional storage methods [10,11]. However, metal silos are relatively expensive compared to other storage techniques, so smallholder farmers would require credit or a subsidy to purchase these structures.

Table 5. Advantages and disadvantages of different grain storage practices for smallholder farmers.

Storage System	Advantages	Disadvantages	Cost	Grain Quality and Losses after Storage
Conventional woven polypropylene sack	Simple to use Available in different storage capacities Occupy less space	Do not last long Easy access to pests and rodents Susceptible to water	US$ 0.65 per 90 kg poly bag [39] US$ 1.6 for jute bags	Low quality, High loss
Conventional granary	Simple to make and use Available in different storage capacities.	Occupy large space all time Do not last long Pests, insects, and rodents can get into the structure easily	About US$ 10 [34] for approx. 500 kg storage capacity	Low quality High loss
Chemicals	Can be effective if applied at correct doses Ease of use flexible	Potential health hazards	Actellic super cost US$ 3.3 per 90 kg bag [39] Need to apply every 3 months	Low quality Low loss
Hermetic metal silo	Simple to design and construct Easy to use Durable	Metal sheets are expensive High skills required for construction	US$ 29 for 90 kg capacity US$ 243 for 1.8 ton capacity	High quality, Low loss
Hermetic bags	Low cost of production Simple, flexible, and durable Easy to use	Can be destroyed by sharp objects, pest, and rodents	US$ 3 for PICS bag US$ 5.3 for 90 kg SuperGrainBag [39]	High quality, Low loss
Self-build silo	Uses local materials Very durable Simple to construct	Remain fixed at one point outside the house	-	-
On-farm and condominium storage structures	Can be owned or rented by farmers Cost effective for farmers in developed countries	Farmers incur both fixed and variable costs Investment and operations costs are high for smallholder farmers in developing countries	Storage cost of US$ 0.03 per sack per year paid to operators [1]	Quality and losses depends on storage conditions

[1] Information based on personal communication with local farmers in southern India.

6. Desirable Features of an Improved Grain Storage System

The most important feature of grain storage systems is the ability to store grain for an extended period of time, preferably several months, with minimal loss in grain quantity and quality. Improved storage structures appropriate for smallholder farmers should be simple, easy to manufacture and use, and the construction materials should be locally available. It should also ensure enough strength and durability that it could be reused to effectively and efficiently store grain for multiple years. The improved storage system should be designed for in-home use because most smallholder farmers in developing countries like to store their grain within their living space to ensure security [8]. The initial capital investment costs and complexity of the technology are major constraints to the adoption of storage systems by smallholder farmers in developing countries. Thus, the appropriate grain storage solution for these farmers should meet the following criteria: (1) provide effective storage conditions for grain; (2) availability in the local market; (3) ease of placing inside residential units, and (4) ease of moving from one point to another. Such an improved grain storage system will reduce losses and maintain quality to ensure food security.

7. Conclusions

Different grain storage practices are adopted by smallholder farmers in developing countries globally. Conventional storage practices include gunny bags, woven granaries and cribs, and wooden boxes. Different locally available plant leaves, oil and ashes, as well as chemicals, are also used during grain storage. In addition to these, larger-scale community-based grain storage practices are also adopted by smallholder farmers. More recent technologies, such as hermetic metal silos and multilayer bagging systems, have also been promoted in developing countries. Hermetic metal silos, multilayer bagging systems, and chemical use result in significantly lower grain losses during storage of grain compared to the conventional storage systems. The design of new storage options should focus on ensuring maximum air-tightness to maintain hermetic conditions. This type of storage has a lower grain loss compared to the conventional storage methods. In the future, smallholder farmers in developing countries could benefit from new grain storage technologies that use locally available materials, involve low cost, and maintain hermeticity.

Acknowledgments: This work was supported in part by funding from the United States Agency for International Development (USAID)-funded Innovative Agricultural Research Initiative project (iAGRI) (Award No. CA-621-A-00-11-00009-00), NSF—iCorps Federal Award No.: 1322061 (Subaward No.: 535326-OSU 8), and USDA NIFA Hatch project 1005665. The opinions expressed herein are those of the authors and do not necessarily reflect the views of the sponsoring agencies. The authors thank Ms. Mary Wicks (Food, Agricultural and Biological Engineering Department, The Ohio State University) for critical review.

Author Contributions: Ashish Manandhar reviewed existing literature and wrote the manuscript. Paschal Milindi reviewed existing literature and contributed in some sections of the manuscript. Ajay Shah conceived the idea and provided critical suggestions throughout the manuscript development process. All authors reviewed the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Food and Agriculture Organization. *The State of Food and Agriculture: Innovation in Family Farming*; Food and Agriculture Organization: Rome, Italy, 2014.
2. Food and Agriculture Organization. *Smallholders and Family Farmers*; Food and Agriculture Organization: Rome, Italy, 2012.
3. Leff, B.; Ramankutty, N.; Foley, J.A. Geographic distribution of major crops across the world. *Glob. Biogeochem. Cycles* **2004**, *18*. [CrossRef]
4. Abass, A.B.; Ndunguru, G.; Mamiro, P.; Alenkhe, B.; Mlingi, N.; Bekunda, M. Post-harvest food losses in maize-based farming system of semi-arid savannah area of Tanzania. *J. Stored Prod. Res.* **2014**, *57*, 49–57. [CrossRef]
5. Pedrick, C. *Going to Waste—Missed Opportunities in the Battle to Improve Food Security*; The Technical Centre for Agricultural and Rural Cooperation: Wageningen, The Netherlands, 2012.
6. Food and Agriculture Organization. *Global Food Losses and Food Waste—Extent, Causes and Prevention*; Food and Agriculture Organization: Rome, Italy, 2011; ISBN 9789251072059.
7. Kumar, D.; Kalita, P. Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries. *Foods* **2017**, *6*, 8. [CrossRef] [PubMed]
8. Sergiy, Z.; Nancy, M.; Luz, D.R.; Rick, H.; Ben, B.; Tanya, S.; Paul, M.; John, L. *Missing Food: The Case of Postharvest Grain Losses in Sub-Saharan Africa*; The World Bank: Washington, DC, USA, 2011.
9. Hodges, R.J. Postharvest Quality Losses of Cereal Grains in Sub-Saharan Africa. *Afr. Postharvest Losses Inf. Syst.* **2012**, *22*.
10. De Groote, H.; Kimenju, S.C.; Likhayo, P.; Kanampiu, F.; Tefera, T.; Hellin, J. Effectiveness of hermetic systems in controlling maize storage pests in Kenya. *J. Stored Prod. Res.* **2013**, *53*, 27–36. [CrossRef]
11. Chigoverah, A.A.; Mvumi, B.M. Efficacy of metal silos and hermetic bags against stored-maize insect pests under simulated smallholder farmer conditions. *J. Stored Prod. Res.* **2016**, *69*, 179–189. [CrossRef]
12. Nganga, J.; Mutungi, C.; Imathiu, S.; Affognon, H. Effect of triple-layer hermetic bagging on mould infection and aflatoxin contamination of maize during multi-month on-farm storage in Kenya. *J. Stored Prod. Res.* **2016**, *69*, 119–128. [CrossRef]
13. ICVolunteers Cowpea. Available online: www.agriguide.org/index.php?what=agriguide&id=161&language=en (accessed on 19 March 2018).
14. Uhrig, J.W.; Maier, D.E. Costs of Drying High-Moisture Corn. Available online: https://www.extension.purdue.edu/extmedia/gq/gq-3.html (accessed on 17 March 2018).
15. Proctor, D.L. *Grain Storage Techniques: Evolution and Trends in Developing Countries*; Food and Agriculture Organization: Rome, Italy, 1994.

16. Lindblad, C. *Programming and Training for Small Farm Grain Storage. Appropriate Technologies for Development. Manual No. M-2B*; Burton International School: Detroit, MI, USA, 1981.
17. Fields, P.G. The control of stored-product insects and mites with extreme temperatures. *J. Stored Prod. Res.* **1992**, *28*, 89–118. [CrossRef]
18. Eeckhout, M.; Landschoot, S.; Deschuyffeleer, N.; De Laethauwer, S.; Haesaert, G. Guidelines for Prevention and Control of Mould Growth and Mycotoxin Production in Cereals. 2013. Available online: http://synagra.be/Download.ashx?ID=6421 (accessed on 16 November 2017).
19. North Carolina Public Health. Mold: Where It Can Grow. Available online: http://epi.publichealth.nc.gov/oee/mold/grow.html (accessed on 21 December 2017).
20. Hellevang, K.J. Grain Moisture Content Effects and Management. Available online: www.ag.ndsu.edu/pubs/ageng/grainsto/ae905.pdf (accessed on 18 November 2017).
21. Weinberg, Z.G.; Yan, Y.; Chen, Y.; Finkelman, S.; Ashbell, G.; Navarro, S. The effect of moisture level on high-moisture maize (*Zea mays* L.) under hermetic storage conditions in vitro studies. *J. Stored Prod. Res.* **2008**, *44*, 136–144. [CrossRef]
22. Jay, E. Recent advanced in the use of modified atmospheres for the control of stored-product insects. In *Insect Management for Food Storage and Processing*; Baur, F., Ed.; American Association of Cereal Chemists: St. Paul, MN, USA, 1984.
23. Yakubu, A.; Bern, C.J.; Coats, J.R.; Bailey, T.B. Hermetic on-farm storage for maize weevil control in East Africa. *Afr. J. Agric. Res.* **2011**, *6*, 3311–3319.
24. Chi, Y.H.; Ahn, J.-E.; Yun, D.-J.; Lee, S.Y.; Liu, T.-X.; Zhu-Salzman, K. Changes in oxygen and carbon dioxide environment alter gene expression of cowpea bruchids. *J. Insect Physiol.* **2011**, *57*, 220–230. [CrossRef] [PubMed]
25. Navarro, S. Modified atmospheres for the control of stored-product insects and mites. In *Insect Management for Food Storage and Processing*; Elsevier: Amsterdam, The Netherlands, 2006; pp. 105–146.
26. Xihong, R.; Zhanggui, Q.; Yongjian, F.; Shuzhong, F.; Quan, L.; Jin, Z.; Liang, Q.; Liang, Y.; Tan, X.; Guan, L. Effects of oxygen concentration on the mortality of four adult stored-product insects in low dosage phosphine fumigation. In Proceedings of the 7th International Working Conference on Stored-Product Protection, Beijing, China, 14–19 October 1998; pp. 364–366.
27. Kamanula, J.; Sileshi, G.W.; Belmain, S.R.; Sola, P.; Mvumi, B.M.; Nyirenda, G.K.C.; Nyirenda, S.P.; Stevenson, P.C. Farmers' insect pest management practices and pesticidal plant use in the protection of stored maize and beans in Southern Africa. *Int. J. Pest Manag.* **2010**, *57*, 41–49. [CrossRef]
28. Rajendran, S.; Sriranjini, V. Plant products as fumigants for stored-product insect control. *J. Stored Prod. Res.* **2008**, *44*, 126–135. [CrossRef]
29. Mulungu, L.S.; Lupenza, G.; Reuben, S.; Misangu, R.N. Evaluation of botanical products as stored grain protectant against maize weevil, *Sitophilus zeamais* (L.), on maize. *J. Entomol.* **2007**, *4*, 258–262.
30. Porter, J.H.; Parry, M.L.; Carter, T.R. The potential effects of climatic change on agricultural insect pests. *Agric. For. Meteorol.* **1991**, *57*, 221–240. [CrossRef]
31. Kisimoto, R.; Dyck, V.A. Climate and rice insects. In Proceedings of the Symposium on Climate and Rice; International Rice Research Institute: Los Banos, Philippines, 1976; pp. 367–390.
32. Hagstrum, D. *Stored-Product Insect Resource*; Elsevier: Amsterdam, The Netherlands, 2016.
33. Food and Agriculture Organization. Pests and Diseases Management in Maize, Uganda. Available online: http://teca.fao.org/read/7019 (accessed on 14 December 2017).
34. Phiri, N.; Otieno, G. *Managing Pests of Stored Maize in Kenya, Malawi and Tanzania*; The MDG Centre, East and Southern Africa: Nairobi, Kenya, 2008.
35. Food and Agriculture Organization. Insect Damage: Post-Harvest Operations. Available online: http://www.fao.org/3/a-av013e.pdf (accessed on 12 December 2017).
36. Vowotor, K.A.; Meikle, W.G.; Ayertey, J.N.; Markham, R.H. Distribution of and association between the larger grain borer *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) and the maize weevil *Sitophilus zeamais Motschulsky* (Coleoptera: Curculionidae) in maize stores. *J. Stored Prod. Res.* **2005**, *41*, 498–512. [CrossRef]
37. Jacobs, S.; Calvin, D. *Weevils of Stored Grains*; Entomological Notes; College of Agriculture Sciences Cooperative Extension, Pennsylvania State University: State College, PA, USA, 2001.
38. Rugumamu, C.P. A Technique for Assessment of Intrinsic Resistance of Maize Varieties for the Control of *Sitophilus zeamais* (Coleoptera: Curculionidae). *TaJONAS Tanzan. J. Nat. Appl. Sci.* **2012**, *3*, 481–488.

39. CIMMYT. *Effective Grain Storage for Better Livelihoods of African Farmers Project*; CIMMYT: Texcoco, Mexico, 2011.
40. Food and Agriculture Organization. Insect pests of stored grains in hot climates. Available online: http://www.fao.org/docrep/t1838e/T1838E1f.htm (accessed on 12 January 2017).
41. Quezada, M.Y.; Moreno, J.; Vázquez, M.E.; Mendoza, M.; Méndez-Albores, A.; Moreno-Martínez, E. Hermetic storage system preventing the proliferation of Prostephanus truncatus Horn and storage fungi in maize with different moisture contents. *Postharvest Biol. Technol.* **2006**, *39*, 321–326. [CrossRef]
42. Magan, N.; Lacey, J. Ecological determinants of mould growth in stored grain. *Int. J. Food Microbiol.* **1988**, *7*, 245–256. [CrossRef]
43. Fleurat-Lessard, F. Integrated management of the risks of stored grain spoilage by seedborne fungi and contamination by storage mould mycotoxins—An update. *J. Stored Prod. Res.* **2017**, *71*, 22–40. [CrossRef]
44. Food and Agriculture Organization. Mycotoxins in Grains. Available online: www.fao.org/Wairdocs/X5008E/X5008e00.htm#Contents (accessed on 7 January 2017).
45. Montgomery, M. Molds in Stored Grains. Available online: http://web.extension.illinois.edu/state/newsdetail.cfm?NewsID=28028 (accessed on 7 January 2017).
46. Foroud, N.A.; Eudes, F. Trichothecenes in cereal grains. *Int. J. Mol. Sci.* **2009**, *10*, 147–173. [CrossRef] [PubMed]
47. Pfohl-Leszkowicz, A.; Manderville, R.A. Ochratoxin A: An overview on toxicity and carcinogenicity in animals and humans. *Mol. Nutr. Food Res.* **2007**, *51*, 61–99. [CrossRef] [PubMed]
48. European Union. *Opinion of the Scientific Committee on Food on Fusarium Toxins. Part 4: Nivalenol*; European Union: Brussels, Belgium, 2000.
49. Gitonga, Z.M.; De Groote, H.; Kassie, M.; Tefera, T. Impact of metal silos on households' maize storage, storage losses and food security: An application of a propensity score matching. *Food Policy* **2013**, *43*, 44–55. [CrossRef]
50. Wambugu, P.W.; Mathenge, P.W.; Auma, E.O.; Van Rheenen, H.A. Efficacy of traditional maize (*Zea mays* L.) seed storage methods in western Kenya. *Afr. J. Food Agric. Nutr. Dev.* **2009**, *9*. [CrossRef]
51. Ndegwa, M.K.; De Groote, H.; Gitonga, Z.M.; Bruce, A.Y. Effectiveness and economics of hermetic bags for maize storage: Results of a randomized controlled trial in Kenya. *Crop Prot.* **2016**, *90*, 17–26. [CrossRef]
52. Baoua, I.B.; Amadou, L.; Margam, V.; Murdock, L.L. Comparative evaluation of six storage methods for postharvest preservation of cowpea grain. *J. Stored Prod. Res.* **2012**, *49*, 171–175. [CrossRef]
53. Baoua, I.B.; Amadou, L.; Lowenberg-Deboer, J.D.; Murdock, L.L. Side by side comparison of GrainPro and PICS bags for postharvest preservation of cowpea grain in Niger. *J. Stored Prod. Res.* **2013**, *54*, 13–16. [CrossRef]
54. Freitas, R.S.; Faroni, L.R.A.; Sousa, A.H. Hermetic storage for control of common bean weevil, Acanthoscelides obtectus (Say). *J. Stored Prod. Res.* **2016**, *66*, 1–5. [CrossRef]
55. Mlambo, S.; Mvumi, B.M.; Stathers, T.; Mubayiwa, M.; Nyabako, T. Field efficacy of hermetic and other maize grain storage options under smallholder farmer management. *Crop Prot.* **2017**, *98*, 198–210. [CrossRef]
56. Naik, S.N.; Kaushik, G. Grain Storage in India: An Overview. Available online: http://www.vigyanprasar.gov.in/Radioserials/GrainStorageinIndiabyProf.S.N.Naik,IITDelhi.pdf (accessed on 7 November 2017).
57. Nukenine, E.N. Stored product protection in Africa: Past, present and future. *Julius Kühn Arch.* **2010**, *425*, 26.
58. Moreno, L.L.; Tuxill, J.; Moo, E.Y.; Reyes, L.A.; Alejo, J.C.; Jarvis, D.I. Traditional maize storage methods of Mayan farmers in Yucatan, Mexico: Implications for seed selection and crop diversity. *Biodivers. Conserv.* **2006**, *15*, 1771–1795. [CrossRef]
59. Ganesh, K.K.C. Farm Level Grain Storage Pest Management in Nepal. Available online: http://www.fao.org/docrep/x5048e/x5048E12.htm (accessed on 20 February 2018).
60. Shengbin, L. Study on farm grain storage in China. In Proceedings of the 9th International Working Conference on Stored-Product Protection, ABRAPOS, Passo Fundo, RS, Brazil, 15–18 October 2006.
61. Paliwal, R.L. *El Maíz en los Trópicos: Mejoramiento y Producción*; Food and Agriculture Organization: Rome, Italy, 2001.
62. Dunkel, F.V. Underground and Earth Sheltered Food Storage: Historical, Geographic, and Economic Considerations. Available online: http://about.elsevier.com/media/tust-vsi/v9i5pp310-315.pdf (accessed on 28 March 2018).
63. Nagnur, S.; Channal, G.; Channamma, N. Indigenous grain structures and methods of storage. *Indian J. Tradit. Knowl.* **2006**, *5*, 114–117.

64. Nduku, T.M.; De Groote, H.; Nzuma, J.M. Comparative Analysis of Maize Storage Structures in Kenya. In Proceedings of the 2013 AAAE Fourth International Conference, Hammamet, Tunisia, 22–25 September 2013.
65. Murdock, L.L.; Seck, D.; Ntoukam, G.; Kitch, L.; Shade, R.E. Preservation of cowpea grain in sub-Saharan Africa—Bean/Cowpea CRSP contributions. *Field Crop. Res.* **2003**, *82*, 169–178. [CrossRef]
66. Negi, T.; Solanki, D. Tradition Grain Storage Structures and Practices Followed by Farm Families of Kumaon Region in Uttarakhand. *Indian Res. J. Ext. Educ.* **2015**, *15*, 137–141.
67. Bett, C.; Nguyo, R. Post-harvest storage practices and techniques used by farmers in semi-arid eastern and central Kenya. In Proceedings of the 8th African Crop Science Society Conference, El-Minia, Egypt, 27–31 October 2007; Volume 8, pp. 1023–1227.
68. Rajashekar, Y.; Bakthavatsalam, N.; Shivanandappa, T. Botanicals as grain protectants. *Psyche A J. Entomol.* **2012**, *2012*, 646740. [CrossRef]
69. Kumar, S.; Mohapatra, D.; Kotwaliwale, N.; Singh, K.K. Vacuum Hermetic Fumigation: A review. *J. Stored Prod. Res.* **2017**, *71*, 47–56. [CrossRef]
70. Hodges, R.J. The biology and control of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae)—A destructive storage pest with an increasing range. *J. Stored Prod. Res.* **1986**, *22*, 1–14. [CrossRef]
71. Lv, J.; Jia, S.; Liu, C.; Zhu, Q.; Liu, Q.; Zhang, Z.; Liu, S.; Zhang, J. Electively applying Phosphine fumigation technology in Tianjin area of China. In Proceedings of the 9th International Working Conference on Stored-Product Protection, ABRAPOS, Passo Fundo, RS, Brazil, 15–18 October 2006; pp. 600–604.
72. Danga, S.P.Y.; Nukenine, E.N.; Fotso, G.T.; Adler, C. Use of NeemPro®, a neem product to control maize weevil *Sitophilus zeamais* (Motsch.) (Coleoptera: Curculionidae) on three maize varieties in Cameroon. *Agric. Food Secur.* **2015**, *4*, 18. [CrossRef]
73. Dowell, F.E.; Dowell, C.N. Reducing grain storage losses in developing countries. *Qual. Assur. Saf. Crop. Foods* **2017**, *9*, 93–100. [CrossRef]
74. Collins, P.J. Resistance to chemical treatments in insect pests of stored grain and its management. In Proceedings of the 9th International Working Conference on Stored Product Protection, Campinas, São Paulo, Brazil, 15–18 October 2006; pp. 277–282.
75. Benhalima, H.; Chaudhry, M.Q.; Mills, K.A.; Price, N.R. Phosphine resistance in stored-product insects collected from various grain storage facilities in Morocco. *J. Stored Prod. Res.* **2004**, *40*, 241–249. [CrossRef]
76. Harish, G.; Nataraja, M.V.; Ajay, B.C.; Holajjer, P.; Savaliya, S.D.; Gedia, M.V. Comparative efficacy of storage bags, storability and damage potential of bruchid beetle. *J. Food Sci. Technol.* **2014**, *51*, 4047–4053. [CrossRef] [PubMed]
77. Stevenson, P.C.; Nyirenda, S.P.; Mvumi, B.; Sola, P.; Kamanula, J.M.; Sileshi, G.; Belmain, S.R. Pesticidal plants: A viable alternative insect pest management approach for resource-poor farming in Africa. In *Biopesticides in Environment and Food Security: Issues and Strategies*; Scientific Publishers: Valencia, CA, USA, 2012.
78. Sola, P.; Mvumi, B.M.; Ogendo, J.O.; Mponda, O.; Kamanula, J.F.; Nyirenda, S.P.; Belmain, S.R.; Stevenson, P.C. Botanical pesticide production, trade and regulatory mechanisms in sub-Saharan Africa: Making a case for plant-based pesticidal products. *Food Secur.* **2014**, *6*, 369–384. [CrossRef]
79. Barbari, M.; Monti, M.; Rossi, G.; Simonini, S.; Guerri, F.S. Self-build silos for storage of cereals in African rural villages. *Afr. J. Agric. Res.* **2014**, *9*, 1384–1390.
80. Said, P.P.; Pradhan, R. Food Grain Storage Practices—A Review. *J. Grain Process. Storage* **2014**, *1*, 1–5.
81. Edwards, W. *Grain Storage Alternatives: An Economic Comparison*; Ag Decision Maker, Iowa State University Extension: Ames, IA, USA, 2015; pp. 1–7.
82. India Agronet. Storage and Warehousing. Available online: www.indiaagronet.com/indiaagronet/Agri_marketing/contents/StorageandWarehousing.htm (accessed on 2 January 2017).
83. Garg, M.K. CAP storage, an economic warehousing technique. In Proceedings of the Conference of International Federation of Public Warehousing Association, London, UK, 1985.
84. Tefera, T.; Kanampiu, F.; De Groote, H.; Hellin, J.; Mugo, S.; Kimenju, S.; Beyene, Y.; Boddupalli, P.M.; Shiferaw, B.; Banziger, M. The metal silo: An effective grain storage technology for reducing post-harvest insect and pathogen losses in maize while improving smallholder farmers' food security in developing countries. *Crop Prot.* **2011**, *30*, 240–245. [CrossRef]
85. Martinez, J.B. *Metal Silos and Food Security. Lessons Learned from a Successful Central American Post-Harvest Program*; Swiss Agency for Development and Cooperation: Quito, Ecuador, 2009.

86. Bala, A.; Kaur, K. An Exploratory study on selected household food storage practices of women in Punjab. *J. Community Mobil. Sustain. Dev.* **2015**, *10*, 70–75.
87. Anankware, P.J.; Fatunbi, A.O.; Afreh-Nuamah, K.; Obeng-Ofori, D.; Ansah, A.F. Efficacy of the multiple-layer hermetic storage bag for biorational management of primary beetle pests of stored maize. *Acad. J. Entomol.* **2012**, *5*, 47–53.
88. Bbosa, D.; Brumm, T.J.; Bern, C.J.; Rosentrater, K.A.; Raman, D.R. Evaluation of Hermetic Maize Storage in 208 Liter (55 Gal) Steel Barrels for Smallholder Farmers. *Trans. ASABE* **2017**, *60*, 981–987. [CrossRef]
89. Hell, K.; Edoh Ognakossan, K.; Lamboni, Y. PICS hermetic storage bags ineffective in controlling infestations of *Prostephanus truncatus* and *Dinoderus* spp. in traditional cassava chips. *J. Stored Prod. Res.* **2014**, *58*, 53–58. [CrossRef]
90. SDC. Central America: Fighting Poverty with Silos and Job Creation. Available online: https://www.shareweb.ch/site/Agriculture-and-Food-Security/focusareas/Documents/phm_sdc_latin_brief_silos_central_america_e.pdf (accessed on 10 January 2017).
91. Ognakossan, K.E.; Tounou, A.K.; Lamboni, Y.; Hell, K. Post-harvest insect infestation in maize grain stored in woven polypropylene and in hermetic bags. *Int. J. Trop. Insect Sci.* **2013**, *33*, 71–81. [CrossRef]
92. Ognakossan, K.E.; Tounou, A.K.; Lamboni, Y.; Hell, K. Economic analysis of alternative maize storage technologies in Kenya. In Proceedings of the Joint 3rd African Association of Agricultural Economists (AAAE) and 48th Agricultural Economists Association of South Africa (AEASA) Conference, Cape Town, South Africa, 19–23 September 2010; pp. 19–23.
93. Bokusheva, R.; Finger, R.; Fischler, M.; Berlin, R.; Marín, Y.; Pérez, F.; Paiz, F. Factors determining the adoption and impact of a postharvest storage technology. *Food Secur.* **2012**, *4*, 279–293. [CrossRef]
94. Smale, M.; Jayne, T. *Maize in Eastern and Southern Africa: "Seeds" of Success in Retrospect*; Environment and Production Technology Division, International Food Policy Research Institute: Washington, DC, USA, 2003.
95. Cardoso, M.L.; Bartosik, R.E.; Rodriguez, J.C.; Ochandio, D. Factors affecting carbon dioxide concentration in interstitial air of soybean stored in hermetic plastic bags (silo-bag). In Proceedings of the 8th International Conference on Controlled Atmosphere and Fumigation in Stored Products, Chengdu, China, 21–26 September 2008.
96. Cardoso, L.; Bartosik, R.; Campabadal, C.; De La Torre, D. *Air-Tightness Level in Hermetic Plastic Bags (Silo-Bags) for Different Storage Conditions*; Navarro, S., Banks, H.J., Jayas, D.S., Bell, C.H., Eds.; Instituto Nacional de Tecnología Agropecuaria: Balcarce, Spain, 2012; pp. 583–589.
97. De Bruin, T.; Villers, P.; Wagh, A.; Navarro, S. Worldwide use of hermetic storage for the preservation of agricultural products. In Proceedings of the 9th International Controlled Atmosphere & Fumigation Conference (CAF), Antalya, Turkey, 15–19 October 2012; pp. 1–8.
98. Murdock, L.L.; Baoua, I.B. On Purdue Improved Cowpea Storage (PICS) technology: Background, mode of action, future prospects. *J. Stored Prod. Res.* **2014**, *58*, 3–11. [CrossRef]
99. Baributsa, D.; Lowenberg-DeBoer, J.; Murdock, L.; Moussa, B. Profitable chemical-free cowpea storage technology for smallholder farmers in Africa: Opportunities and challenges. *Julius Kühn Arch.* **2010**, *425*, 1046–1052.
100. Baoua, I.B.; Margam, V.; Amadou, L.; Murdock, L.L. Performance of triple bagging hermetic technology for postharvest storage of cowpea grain in Niger. *J. Stored Prod. Res.* **2012**, *51*, 81–85. [CrossRef]
101. García-Lara, S.; Ortíz-Islas, S.; Villers, P. Portable hermetic storage bag resistant to Prostephanus truncatus, Rhyzopertha dominica, and Callosobruchus maculatus. *J. Stored Prod. Res.* **2013**, *54*, 23–25. [CrossRef]