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Review

Postharvest losses in food grains – A Review

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ABSTRACT

Grains (cereals and legumes) are universal foods that provide calories, proteins, essential minerals and vitamins. They are essential to the nutrition of many including infants and children. Attack by insects and microorganisms, particularly fungi, during drying, storage and processing, affects the quality, safety and market value of grains. Fungal attacks before or during drying can be disastrous, the effect can persist throughout the supply chain. Postharvest grain losses pose challenges to food and nutritional security, public health, and many developing nations' economy. Postharvest storage structures and packaging materials are expected to extend the shelf life of the grains by protecting them from insects, microorganisms, environmental factors and making the microenvironment unfavorable for insect and microbial activities. Traditional storage and packaging materials are highly inefficient in this sense and are associated with quality degradation. Traditional storage and packaging materials commonly used by farmers, mostly in developing countries, include granary, crib, wooden box, gunny bag and polypropylene woven bag. Modern storage and packaging materials commonly used are metal silo and hermetic bags; they are effective but unfortunately cannot be afforded by most farmers in developing countries. The article reviewed postharvest storage management of cereals and legumes. Literature was gathered through a comprehensive literature review. The use of various traditional storage and packaging materials for grains was debated. Techniques for the prevention of postharvest losses were extensively discussed, emphasis was given to novel technology and the use of natural insecticides. Challenges associated with controlling postharvest losses were also summarised. In the end, research gaps were identified and recommendations were provided about minimizing grain contamination and postharvest losses.

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1. Introduction

About 2.7 billion metric tons of cereal were produced in 2020 (Statista, 2021). Cereals and legumes are critical to the nutrition of many, including infants (Achaglinkame et al., 2017). Most grain legumes are rich in proteins and other essential micronutrients (Chibarabada et al., 2017). Combination of cereal and legumes provides diets with adequate calories, essential minerals and almost all essential amino acids (N. P. Singh and Pratap, 2016). Bio-fortified cereals can contain essential nutrients such as Zn and pro-vitamin A (Listman et al., 2019) and can play important roles in solving many nutrition-related health problems (Trono, 2019). Grains are a global staple and the main source of food and energy to many (Khaneghah et al., 2018). They are highly universal due to their ability to thrive under a wide range of environmental conditions (Chibarabada et al., 2017) and are easy to handle and transport (Paul et al., 2020). Postharvest losses (PHLs) can be quantitative, qualitative or economic, but most research on PHLs concentrate more on quantitative losses, with very few reporting qualitative and economic losses (Kitinoja et al., 2018).

2. Grain Storage

Storage is critical to postharvest management, and almost all harvested grains undergo storage before reaching consumers' tables (Hiruy and Getu, 2018b). The grain industry's primary challenge in developing countries is inadequate storage facilities and adequate knowledge and experience on postharvest management of grains (Shlomo Navarro and Navarro, 2016). Storage management of harvested grains and measures to prevent the insect from thriving in stored grains is of great concern to food processing and storage industries (Paul et al., 2020). Storage structures and facilities extend shelf life and reduce PHLs by protecting grains against environmental factors, rodents and insects (Mapfeka et al., 2019). Restriction on the utilization of insecticides during storage makes grains storage more challenging and even under optimum storage conditions, grains can be contaminated by insects (Shlomo Navarro and Navarro, 2016). An acoustic insect detection method will detect both hidden and open insects in stored grains without opening the storage structure. The technology involved the use of sound software that collected insect noise, screened and amplified them, and classified them based on their amplitude (Banga et al., 2019)

Farmers use different storage systems in different locations of the globe, traditional facilities used include granaries, cribs (Mapfeka et al., 2019), gunny bags and wooden boxes (Manandhar et al., 2018). Traditional storage structures are used mainly by smallholder farmers in developing countries (Tibagonzeka et al., 2018). Traditional storage structures are not very reliable, grain quality can easily be compromised and the structure can dilapidate easily (Mapfeka et al., 2019). Traditional storage and handling facilities are ineffective against mold and insects (Kumar and Kalita, 2017; Manandhar et al., 2018; Sankara et al., 2016) and are influenced by the external environment, grains can quickly develop mold during the wet seasons, loss their quality and develop safety issues (Garbaba et al., 2018). Most of the farmers in sub-Saharan Africa chose to store their grains at home after bagging (Hengsdijk and de Boer, 2017). Grains intended for consumption are stored for a longer time (Abdoulaye et al., 2015).

The metal silos are quite effective and can adequately maintain grain quality but cannot be afforded by many farmers in developing countries (Manandhar et al., 2018). Modern storage structures are more expensive and only used by wealthy farmers with small family sizes (Ndiritu and Ruhinduka, 2019). Other problems that mitigate the acceptance of modern storage structures are difficulty transporting them to rural areas, access to spare parts, high maintenance and running cost, limited harvest, and low market value of produce (Tibagonzeka et al., 2018).

2.1. Effects of temperature and moisture during storage on grain qualities

Temperature and moisture content are important variables that determine the success or otherwise of grain storage. The success of many storage facilities depends significantly on the ability to efficiently manage temperature and moisture during storage (Olorunfemi and Kayode, 2021). Maintaining optimum climate conditions in the storage structure is necessary for preserving grain qualities (Gibson et al., 2020). Higher moisture content and elevated temperature are deleterious to the quality of grains (Gilmore et al., 2017; Panigrahi et al., 2020). Moisture content above 12 % is deleterious to grain qualities during storage and can affect safety and quality even under hermetic storage conditions (Likhayo et al., 2018). Wang et al (2020) also reported a linear relationship between moisture content and mildewing in wheat. Drying methods significantly affect the insect population during storage. Asemu et al. (2020) reported that a fabricated solar bubble dryer operated at 52 °C under tropical and subtropical climates could significantly lower moisture content to a safe level disinfect grains without affecting their physicochemical properties.

Fluctuation of environmental conditions can cause variation in the temperature and relative humidity within the storage structure, this occurs more rapidly near the sidewalls of the storage structure (Chen et al., 2015; Quemada-Villagómez et al., 2020). The findings of Garg et al. (2016) revealed that the moisture content of wheat packaged in metallic bins and jute bags responds to environmental moisture change. Angelovič et al. (2018) also reported that extraneous temperature and moisture dictate the moisture content of maize stored in a silo. External conditions can also influence condensate formation on the surface of improperly dried grains (Kechkin et al., 2020). This happens when the grain temperature is above the external temperature (Chen et al., 2015).

Grains undergo many changes during storage. Their nutrients' composition and functionality depend on their moisture content and storage temperature (Meneghetti et al., 2019). Higher moisture during storage favor mold growth and aflatoxins production (Afzal et al., 2017). Singano et al. (2019) opined that climate change could reduce the effectiveness of storage structures in areas that are more prone to climate change. Exposure to higher temperatures during storage can cause molecular degradation of starch as reported by Gu et al. (2019) in rice stored at 25 °C for 12 months. R. Wang et al. (2020) associated nutrient losses in stored wheat with higher moisture and exposure to higher temperatures during storage. Moisture uptake during storage affects wheat's color index and water activity (Rajak et al., 2017). Reduction in protein extractability, solubility and isoflavones content were observed in soybeans stored at higher temperatures and higher moisture (Ziegler et al., 2018). Higher moisture during storage alters the fatty acid composition of soybean oil (Ziegler et al., 2016). Atungulu et al. (2017) reported that storage under reduced-oxygen conditions slows down rice dry matter losses.

One of the significant challenges in grain storage is monitoring and controlling storage conditions, particularly during prolonged storage. The recent application of IoT in monitoring and controlling temperature, relative humidity, gases concentration, etc., in stores will certainly provide solutions to the numerous grain storage challenges. Kodali et al. (2020) demonstrate the possibility of monitoring and controlling storage conditions using sensors, controllers and the internet. Martyn et al. (2019) developed a wireless system for monitoring temperature and relative humidity in the atmosphere of storage structures and dryers. Asefi et al. (2017) and Gilmore et al. (2017) developed an Electromagnetic Imaging system for detecting spoilage in large capacity grain storage structures. Q. Wang et al. (2020) invented a procedure for predicting grains temperature during storage using surrounding air temperature.

3. Postharvest Losses of Grains

About 32 % (1.3 billion tonnes) of the food produced for human consumption gets lost or wasted every year (Kitinoja et al., 2018; Kumar and Kalita, 2017; Tomlins et al., 2016). Fortunately, cereals and oilseeds have the lowest overall global losses ranging between 9 - 18 % (Janila et al., 2016; Mezgebe et al., 2016; Tomlins et al., 2016). Most of the PHLs occur between harvest and consumption (Bradford et al., 2018). On-farm PHLs account for about 5 % (Arun and Ghimire, 2019), and storage losses account for 6-10 % (Chegere, 2018; Janila et al., 2016). Storage account for the highest PHLs in developing countries (Shisiali, 2018). Chegere (2018) reported 2.9 % lost between harvest and storage of maize in sub-Saharan Africa and 1.1 % lost during marketing. Inefficient handling and storage technology account for the massive grains PHLs in developing countries (Kumar and Kalita, 2017). In some places, storage can account for more than 10 % lost. For instance, in Ethiopia, 31 % loss was reported in maize by Garbaba et al. (2018) during 6 months storage, in Nigeria, 10 to 30 % loss was reported by Danbaba et al. (2019) in the rice supply chain in Kenya, 17.6 % lost was associated with off-farm storage (Mwangi et al., 2017). Grain PHLs of 30 % were reported by Baoua et al. (2014) in four West African countries, Tibagonzeka et al. (2018) reported 17-41 % in Uganda and Befikadu (2018) reported 50 % in Ethiopia.

3.1. The need for reducing postharvest losses

There is an urgent need to curtail PHLs due to accelerated population growth, climate change, and the continuous diminishing of essential natural resources (Arun and Ghimire, 2019; Schmidt et al., 2018). Increasing 2.4 % in significant crop yield is required to meet the global food demand by 2050 (Nawaz and Chung, 2020). Grain losses due to insect infestation are paramount to the African economy and the world (Adarkwah et al., 2017). Reducing PHLs is essential in improving food security and increasing farm income (Chegere, 2018; Kumar and Kalita, 2017). It is also a synonym for increasing agricultural production (Arun and Ghimire, 2019; Stathers et al., 2020).

PHLs of grains are a significant threat to food security in many developing countries (Hiruy and Getu, 2018b; Manandhar et al., 2018). Food production in most of these countries is below the national demand (Befikadu, 2018) and there are no well-established infrastructures, guidelines, and standards in most developing countries (Neme and Mohammed, 2017). Unlike in developed nations, where PHLs occur during distribution and consumption, PHLs occur during harvest, postharvest handling and storage (Swai et al., 2019). In developing countries, food wastes and losses are usually discarded, while in countries with emerging and developing economy they are converted to useful substances such as ethanol (Melikoglu and Turkmen, 2019).

3.2. Causes of postharvest losses

Deterioration of grains after harvesting is a global issue and it commonly occurs during storage and transportation (García-Mosqueda et al., 2019; Xue et al., 2017). PHLs of grains are caused by pest infestation and microbial and rodents attacks (Mapfeka et al., 2019; Mezgebe et al., 2016; Quellhorst et al., 2020; Schmidt et al., 2018). The fungal attack is the most disastrous, and it causes losses and health-threatening problems in improperly dried grains (Garbaba et al., 2018). Attack by fungi and pests depreciates grain qualities during medium and long-term storage (Lorenzo et al., 2020). All postharvest insects have exceptionally high growth and proliferation rate (Said and Pashte, 2015).

The major factors account for PHLs of grains are infestation by insect–pests, rodents, imprudent store–time, unjustifiable marketing models (Swai et al., 2019), poor storage and transportation facilities (Janila et al., 2016; Swai et al., 2019; Tibagonzeka et al., 2018), spillage due to inadequate handling, transportation and packaging facilities, reused packaging materials (Mwangi et al., 2017), use of uncertified seeds (Njonjo et al., 2019), planting mixed variety of seeds, mixing old and new seeds, harsh weather conditions, farmers disunity, limited access to loans, inadequate on-farm storage facilities (Tibagonzeka et al., 2018), limited output, access to the market (Amentae et al., 2016), bad roads, annual average rainfall (Hengsdijk and de Boer, 2017), limited access to vital farm inputs (Gunasekera et al., 2017), lack of sufficient postharvest management intervention (Quellhorst et al., 2020; Fabi et al., 2021), lack of improved crop variety and inappropriate storage condition (Kumari et al., 2020).

Insect infestation is among the leading biotic factors that deteriorate grains during storage (Banga et al., 2020; Hiruy and Getu, 2018b). Insects cause both quantitative and qualitative losses during cereals, legumes and oilseeds (Banga et al., 2020). Moreover, postharvest insect infestation is detrimental to grain processing qualities (Banga et al., 2020) and can develop objectionable flavors and odors (Said and Pashte, 2015). Coleopterous weevils and Lepidopterous stalk borers are the most devastating insects in both fields and stores (Hiruy and Getu, 2018b). Many insects are pathogenic, they also transmit diseases and physical destruction (Seetharamu et al., 2020).

The major insects for stored cereals are lesser grain borer (*Rhyzopertha dominica*), granary weevil (*Sitophilus granarius* L.), rice weevil (*Sitophilus oryzae* L.), maize weevil (*Sitophilus zeamais Motschulsky*), rusty grain beetle (*Cryptolestes ferrugineus*), flour mill beetle (*Cryptolestes turcicus*), merchant grain beetle (*Oryzaephilus mercator*), saw-toothed grain beetle (*Oryzaephilus surinamensis* L.), long headed flour beetle (*Latheticus oryzae*), red flour beetle (*Tribolium castaneum*), confused flour beetle (*Tribolium confusum*), Large flour beetle (*Tribolium destructor Uyttenboogaar*), Angoumois grain moth (*Sitotroga cerealella*), Indian meal moth (*Plodia interpunctella*), and Yellow mealworm (*Tenebrio molitor* L). That stored legumes are bean weevil (*Acanthoscelides obtectus*), pea weevil (*Bruchus pisorum*), cowpea beetle (*Callosobruchus maculatus*), pulse beetle (*Callosobruchus chinensis* L.) and flat grain beetle (*Cryptolestes pusillus*). The typical insect pest of oilseeds is the Khapra beetle (*Trogoderma granarium*) (Banga et al., 2020).

The gas composition of the storage atmosphere affects insect activities in general. Insect activities significantly decrease under a CO_2 saturated atmosphere and higher temperature (Carvalho et al., 2019). A modified atmosphere with higher CO_2 and low O_2 concentrations provides a safe condition for grain storage (Dowell and Dowell, 2017). The reproduction potentials of stubborn insects can be blocked by modifying the storage atmosphere. Carvalho et al. (2019) observed changes in the response of stored-product insects under different O_2 and CO_2 concentrations. The findings of Diarra and Amoah (2019) revealed that hermetic bagging could increase storage temperature to 27 °C and lower O_2, R.H. and moisture to 6.4 %, <70 % and <14 %, respectively in tropical areas, creating an atmosphere unfavorable to insect activities and mold growth.

Improper handling can affect the integrity of grains packaging and affect their permeability. Exposure to extreme environmental conditions degrade packaging materials and facilitate insect and fungal activities (Baoua et al., 2018). Chelladurai et al. (2016) reported that stretching during loading and offloading, exposure to sunlight and prolonged storage can affect the O_2 and CO_2 uptake pattern of silo bags.

3.3. Controlling postharvest losses

Insect infestation can be controlled by proper pre-and postharvest management using safe and affordable techniques (Hiruy and Getu, 2018b). Adequate cleaning and sanitation are important prevention measures. They can eliminate pests, dormant eggs and immature organisms (Paul et al., 2020). Infestation techniques must align with regulatory safety measures and market specifications before acceptance (Paul et al., 2020). Disinfection capacity, safety and environmental concern are the significant factors designating the efficiency of insect control (Paul et al., 2020). It is essential to understand insect behavior, growth requirement, and lifecycle in eliminating them (Banga et al., 2020). Insects dispersal patterns and walking behavior are essential in understanding their distribution and population dynamics (Vélez et al., 2019). In addition, understanding the disinfection principles of control measures is also crucial in avoiding insect resistance to the treatment (Paul et al., 2020).

Incessant insecticide resistance demonstrated by storage insects continues to be the major challenge in preventing PHLs (Umina et al., 2019). This necessitate the constant search for alternative pesticides (Vélez et al., 2017). Different traditional methods were used for pest control in stored grains. Most of these traditional methods were improved and co-opted into modern control (Tripathi, 2018). Different plant materials include oils and ashes and synthetic chemicals, are also used to improve the storability of grains (Manandhar et al., 2018). Multilayer bagging systems and hermetic metallic silos are the recently developed technologies promoted in developing countries (Manandhar et al., 2018).

Creating awareness on the importance of using recommended P.H. handling and storage techniques will surely mitigate PHLs (Chegere, 2018). Many farmers are ready to embrace novel techniques when economic benefits are demonstrated and proven beyond reasonable doubt (Egessa et al., 2017). A modified marketing system with stricter quality requirements can improve the postharvest qualities of grains as proved by Minten et al. (2021). Improved storage facilities with real-time alerts on R.H. and temperature will certainly reduce PHLs (Shisiali, 2018). The quality-quantity spoil of grains produced in developing countries started at the farm. Therefore, effective remedies should be initiated at the farm level (Befikadu, 2018).

The success of any postharvest management can be measured by farmers' and agro entrepreneurs' ability to have access to finance (Egessa et al., 2017). These areas of postharvest are receiving less attention when compared with production. Most interventions are directed to production, with little allocated to postharvest physiology and storage (Hiruy and Getu, 2018b). Intervention on PHLs prevention should also target stakeholders other than farmers along the supply chains (Stathers et al., 2020). The approaches used in mitigating PHLs are stated below.

3.3.1. Synthetic chemicals

Grains are mixed with synthetic chemicals to maintain their quality during storage (Manandhar et al., 2018). Chemical pesticides efficiently prevent postharvest infestation, but their toxicity and persistence are of great concern (Akinneye et al., 2018). The most common fumigants used for insect control in grains during storage are Phosphine, Sulfuryl fluoride, Ethyl formate, Methyl bromide and Ozone. At the same time, organophosphates, organochlorines, carbamates and pyrethroid are the most common synthetic pesticides used (Paul et al., 2020). Spinetoram was effective against *Sitophilus oryzae* and *Rhyzopertha dominica* at the application rate of 5 and 0.1 ppm, respectively, mortality of both insects was achieved after 14 days (Vassilakos et al., 2015). The use of nano-engineered alumina insecticide powders was reported by Buteler et al. (2020), the powder is removed at the end of storage using a pneumatic system to avoid safety issues. Chiral amides 8i and 8j effectively control *Rhyzopertha dominica*, a common wheat pest (Aguiar et al., 2019).

Synthetic chemical causes many side effects on the environment and humans (Ayalew, 2020). Residual chemicals insecticides in grains were reported to cause health problems (Said and Pashte, 2015). Their indiscriminate use can lead to resistance and revival in insects and leach and contaminate the environment (Seetharamu et al., 2020). Teló et al. (2017) reported the presence of pre-harvest insecticide residues in rice husk. Residues of thiamethoxam and chlorantraniliprole from field treatment were found in husk, bran and polish rice grains (Teló et al., 2015). Akinneye et al. (2018) reported chlorpyrifos concentration above the maximum residue limit in stored bean samples collected from Akure, Nigeria. Rumbos et al. (2018) reported that capsule suspension of pirimiphos-methyl formulations is highly persistent and cannot vanish after seven months of storage in wheat.

Some processing methods were reported to reduce the storage of pesticide residues. Han et al. (2016) showed that soaking, steaming, fermentation and distillation could reduce pesticide residues in grain products. Though a complex and expensive option, the application of ozone is reported to significantly reduce storage pesticide residues in grains (Savi et al., 2015). Residues of bifenthrin were reduced by 37.5 % in pesticide-treated stored wheat after exposure to ozone at 60 µmol/mol for 180 min, while pirimiphos-methyl residues were reduced by 71.1 % after 30 min exposure (Savi et al., 2016). Ozone treatment effectively reduced pirimiphos-methyl residues by 91 % in maize treated with Actellic 500 CE® (de Freitas et al., 2017). Exposing insecticide-treated wheat to ozone at 60 µmol/mol for 120 and 180 min reduces deltamethrin residue by 80.6% and 85.7%, respectively (Savi et al., 2015). An ozone application rate of 3 mg L^{-1} and continuous flow of 1.0 L min^{-1} for ten h reduces the concentration of bifenthrin by 91.9 % and deltamethrin by 92.7 % in pesticides treated rice (de Ávila et al., 2017).

3.3.2. Natural insecticides

Researches on the development of green pesticide from plant and animal extracts and microbes are ongoing (Seetharamu et al., 2020). This class of pesticide is much safer and more biodegradable (Omara et al., 2018). Higher plants such as neem and various herbs and spices such as garlic, clove, turmeric, etc., possessed antimicrobial and insecticidal properties (Said and Pashte, 2015). Essential oils extracted from Sydney Bluegum (*Eucalyptus saligna*) leaves show promising results against maize weevil in both contact and fumigation assay (Omara et al., 2018). Allspice (Pimenta dioica) leaf essential oil destroys cowpea beetle 6 and 12 hours after exposure in contact and fumigation treatments respectively (Tenne and Karunaratne, 2018). *Chenopodium ambrosioides* L. and *Cupressus sempervirens* L. essential oils show insecticidal effects and inhibit fungal spore germination in maize (Langsi et al., 2018). Carvone chemotype and Monoterpene carvone essential oils showed positive insecticidal effects against *Sitophilus zeamais* and *Tribolium castaneum* (Peixoto et al., 2015). Bay leaf essential oil can eliminate storage insect, *Tribolium castaneum* (Chahal et al., 2016). Adarkwah et al. (2017) reported that a combination of diatomaceous earth (Probe-A® DE, 89.0 % SiO2 and 5% silica aerogel) and Eugenia aromatic (fruit and flower bud) and *Moringa oleifera* (leaves) successfully destroyed adult *Sitophilus granarius, Tribolium castaneum* and *Acanthoscelides obtectus* within seven days. Both leaves powder and oil of Lantana Camara were reported to be toxic to an important maize storage insect, *Sitophilus zeamais* (Ayalew, 2020). *Illicium verum* and *Eugenia caryophyllus* essential oils reduce emergence and ovipositor and cause the death of stubborn cowpea weevil *Callossobruchus maculatus* at the lethal concentrations LC50 and LC95 of 9.62 and 32.78, 1.27 and 11.95 µL/20 g, respectively (Matos et al., 2020). Oil produced from pyrolysis of sunflower seed hulls demonstrate higher insecticidal effects against Sitophilus oryzae and induced nutritional physiology effects that caused antifeedant activity in *Tribolium castaneum Sitophilus oryzae* (Urrutia et al., 2021).

Green insecticides are expected to solve insect resistance and environmental safety (Seetharamu et al., 2020). Further researches are needed for a better understanding of the efficacy and applicability of natural pesticides (Said and Pashte, 2015)

3.3.3. Biological control

An unexplored area in PHLs prevention is the application of microorganisms and their products, Buchholz et al. (2018) is optimistic that plant microbiota can provide a solution to PHLs. Batta and Kavallieratos (2017) explained the potentials of entomopathogenic fungi in the control of storage insects, the synergistic effect produced by combining the fungi and diatomaceous earth, chemical insecticides and natural products was excellent. Similarly, the combination of *Beauveria bassiana* (pathogenic insect fungi) and diatomaceous earth successfully suppressed the growth of wheat weevils during long-time storage (Wakil and Schmitt, 2015). Mbata and Warsi (2019) recommended using *Habrobracon hebetor* and *Pteromalus cerealellae* in the biological control of insects during grain storage due to their excellent host searching ability and reproductive performance under a wide range of environmental conditions.

3.3.4. Physical methods

This involves hermetic packaging and the use of insect-desiccants dust. These methods are far safer and provide products with excellent storage qualities (Kalsa et al., 2019; Schmidt et al., 2018). Insect-desiccant dust is powders added to grains during storage. They dehydrate the insect by destroying the waxy outer layer of their exoskeleton (Hiruy and Getu, 2018b). Rock inert dust eradicates maize weevils (*Sitophilus zeamais*) 21 days after exposure under laboratory conditions at the application rate of 5 % and significantly minimizes grain damage and weight loss (Hiruy and Getu, 2018a).

Adopting an air-tight packaging system such as hermetic silos and the use of super grains bags (containing layers of higher density polyethylene) will surely enable farmers to lower PHLs (Groote et al., 2013). Hermetic bags extend the storability of food grains by reducing oxygen content in the bag and increasing carbon dioxide content through respiration of the grain, insects and microbial activities (Vales et al., 2014). They are a safe and effective alternative to synthetic pesticides (Abass et al., 2018). Hermetic silos efficiently mitigate insect population and growth, grain damages, dust formation and weight loss during storage (Chigoverah and Mvumi, 2016) and are more effective than hermetic bags (Groote et al., 2013).

A chemical-free, cheap triple hermetic bagging technology known as Purdue Improved Crop Storage (PICS) developed for cowpea storage is now used for other grains such as maize (Baoua et al., 2014). Grains quality and germination capacity were not affected during the storage in the PICS bag and aflatoxins (A.F.s) contamination was found to be less when compared with traditional polypropylene woven bag (Baoua et al., 2014). PICS bags slow down insect growth, moisture absorption and cross-infestation. It also protects nutritional qualities and maintains market value (Njoroge et al., 2014).

PICS technology is efficient and can preserve grains for at least three years (Swai et al., 2019), depending on the initial quality of the grains. Cowpea stored in a PICS bag possessed better grain quality, higher market value and better germination rate (Baoua et al., 2013). Pigeon pea seeds possess better eating and germination qualities and low A.F.s content after eight months of storage in a PICS bag (Vales et al., 2014). Baoua et al. (2014) reported 95 to 100 % mortality of *Prostephanus truncates* and *Sitophilus zeamais* in maize stored in PICS bags at different locations of the West African region during 6.5 months of storage. Wheat stored in hermetic bags (PICS and SuperGrainPro™ bags) and treated with industrial filter cake dust in polypropylene bags exhibit more than 90 % germination capacity after six weeks of storage (Kalsa et al., 2019). Likhayo et al. (2018) reported only 1.2 % weight loss in properly dried maize stored in an airtight bag during six months of storage. SuperGrainbags™ was found to efficiently destroy many grain harvest insects after four weeks of storage (García-Lara et al., 2013).

A modified atmosphere containing pressurized CO_2 at 8 bar effectively destroys adult and immature *Sitophilus zeamais* and *Tribolium castaneum* in milled rice within five h exposure (Noomhorm et al., 2013).

3.3.5. Novel techniques

The typical novel approaches in preventing grains from pest and microbial contaminations are the use of chemical insecticides, extreme temperature treatments, ozone, irradiation and dielectric heating, metabolic stress disinfestation, non-thermal plasma (Paul et al., 2020), high hydrostatic pressure processing, ultra-sonication, microwave treatments, ultraviolet light and modified atmosphere packaging (Schmidt et al., 2018).

Some of the novel techniques were reported to be inefficient in treating grains against insect infestation and microbial contamination (Schmidt et al., 2018). Some of these techniques have limited industrial applications. For instance, ultrasound treatment does not provide satisfactory results, exposure for 20 min at 30 °C could not inhibit fungal growth during storage (Schmidt et al., 2019). High-pressure processing (HPP) application to grain treatment will be complex due to its higher cost and effectiveness in food with higher moisture content (Schmidt et al., 2019). Negative results were reported in quaternary ammonium compounds, cold plasma and LAB applications (Schmidt, 2018). Uneven heating was reported in grains subjected to radiofrequency heating (Huang et al., 2016).

Nevertheless, the combination of microwave and NaOCl (5%), sorbate and propionate (both 5%, 10 min), high pressure (10 min, 300 MPa, 30°C) treatments and vacuum packing successfully hinder fungal growth and mycotoxin accumulation (Schmidt, 2018). Zhou et al. (2015) achieved 100 % insect motility in milled rice by combining radio frequency, hot air surface heating at 50 °C, adequate mixing and holding for 5 min in a pilot-scale radiofrequency plant.

Positive results were reported on the application of microwave heating in preserving grains. Microwave heating at 370 W for 72 sec raised the temperature at the kernel of beans to 48.9 C and successfully controlled beans weevil (Sosa-Morales et al., 2017). Dalmoro et al. (2015) disinfect wheat and beans without destroying their qualities by exposing them to microwave heating at 1000 W for 1.25 sec. Microwave heating for 3 min at 475 W destroyed the larva of *Sitotroga cerealella* in white maize (García-Mosqueda et al., 2019).

4. Challenges Associated with Controlling Postharvest Losses

PHLs are complicated problems designated by crop type, environmental factors, country location and economy, storage, handling practices (Kumar and Kalita, 2017) and climate change (Mapfeka et al., 2019). Njoroge et al. (2019) reported that controlling pre-harvest pest contamination was virtually impossible in Kenya due to the bimodal rainfall which makes drying very difficult. Deficiencies were reported in recently innovated techniques, including hermetic packaging. Chegere (2018) reported that the cost of some recommended P.H. techniques outweighs their benefits. Insects in heavenly-infested crops can perforate PICS bags and reduce their effectiveness (Baoua et al., 2014; Groote et al., 2013).

Nevertheless, insect-induced perforated hermetic bags perform better than conventional polypropylene bags (Baoua et al., 2014; Chigoverah and Mvumi, 2016). Abass et al. (2018) reported an increase in the moisture content of maize stored under hermetic conditions for 30 weeks. Delay in closing PICS bag after filling can lower its effectiveness and lead to poor quality product (Baoua et al., 2013). Insects vary in their oxygen requirement (Quellhorst et al., 2018). Some can be highly aerobic and can only survive in the presence of ample oxygen, this type of insect can easily be destroyed under hermetic conditions. Insects that require little oxygen for their growth and reproduction can be stubborn under hermetic storage. They can grow and reproduce and subsequently destroy grains and packaging materials before oxygen depletion.

Microwave heating can affect grain qualities. Microwave exposure can severely denature enzymes and gluten in wheat, leading to poor baking qualities (Schmidt et al., 2019). Subjecting beans, lentils and chickpeas to 1000 W microwave heating leads to texture degradation, browning and nutrient losses during soaking and drastically reduces their germination capacity (Dalmoro et al., 2018). More research is required to apply novel techniques such as radiofrequency to bridge the gap between laboratory studies and industrial applications (Hou et al., 2016).

Schmidt (2018) reported that a single treatment could not protect grains from insects and microbial contamination effectively. This can be supported by the findings of Wakil and Schmitt (2015). They reported that a combination of Beauveria bassiana (pathogenic insect fungi), diatomaceous earth (D.E.) and neonicotinoid Imidacloprid provided better control of wheat weevils than using each individually. (Alam et al., 2019) also reported that corn borer Helicoverpa zea can be eliminated by combining Thiamethoxam and Chlorantraniliprole. A practical and holistic approach that will combine pre-and postharvest treatments is needed to provide sustainable solutions (Udomkun et al., 2017). Adopting drying-based and climate-based solutions that will provide perfectly dried grains throughout the supply chain will surely minimize insect and microbial contaminations, prevent A.F.s production, improve grains quality and safety, minimize losses, protect public health and improve food security (Bradford et al., 2018).

5. Recommendations

1. Traditional storage structures can account for up to 50 % loss in some places. Therefore, farmers should be convinced by any means to discard these uneconomical, wasteful, inefficient, laborious and unreliable storage structures.
2. Training farmers on the importance of using improved storage facilities will undoubtedly promote their acceptance.
3. Adoption of mechanical drying will facilitate drying and improve the quality and safety of grains.
4. A hurdle approach can be achieved by incorporation of natural insecticide into hermetic bagging, the two treatments can work synergistically and effectively reduce insect motility time and ensure better and safer grains.
5. PHLs can also be minimized by having a mutual and trusted relationship between farmers and other actors along the supply chain. The farmers have the upper hand in decision marking. This will balance the price of grains year-round.
6. Concern authorities must ensure that monetary intervention and support, technologies and equipment for mitigating PHLs reached the bottom of the supply chain and delivered only to genuine active farmers.
7. Future grain storage and packaging materials should ensure improved air-tightness to guarantee better hermetic conditions.
8. Modified polymer with insect repellent properties as primary packaging material will avoid bag perforation by insects during storage.

9. In-depth research is needed to find solutions to the problems associated with applying novel techniques (such as ultrasound treatment, high-pressure processing and radiofrequency heating) in the disinfection of grains.

10. Data on the utilization of parasitic insects in pest biological control is limited, the area should be explored to provide more sustainable ways of protecting crops.

11. Development of cheaper storage facilities is needed for developing countries since many farmers in these countries cannot afford hermetic metallic silos and hermetic bags.

12. Possibility of incorporating substances that will speed up CO_2 accumulation in hermetic containers should be studied as this will lower insect motility time.

13. Development of computer software that will be sending real-time conditions (on temperature, relative humidity, pests and microbial activities) of the storage structure will reduce PHLs, the technology will allow taking corrective measures on time.

14. Continuous research in grains postharvest management is necessary as insects and microorganisms continue to develop resistance to the existing physical and chemical treatments.

6. Conclusion

Population growth, climate change and ever-depleting natural resources necessitate the need to curtail PHLs. Grain losses due to insect infestation and microbial contamination affect the nutritional status and economy of many countries. Effective postharvest management is necessary to ensure the supply of good quality grains year-round. Provision of adequate and effective storage and packaging material for grains is necessary to prevent their PHLs. The grain industry's primary challenge is inadequate storage facilities that can control the quality of the grains. Farmers in developing countries require special attention as many cannot afford modern storage facilities. Efficient control of PHLs cannot be achieved using a single treatment, an intelligent combination of different treatments based on the pest's behavior, growth pattern and requirements, properties of the grains and storage conditions will provide adequate control. Combining green insecticides with hermetic packaging will provide safer grains. Providing solutions to the identified problems will protect grains, improve their quality and safety, increase food security, enhance the livelihood, increase farmer's income, facilitate international trade and increase government revenue.

Conflict of Interest

The authors declare that they have no conflict of interest.

Authors' Contributions

Nura Abdullahi: Conceptualization, literature search and original draft. **Munir Abba Dandago**: Writing reviewing/editing and proofreading.

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