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Review

Appraisal of Post-Harvest Drying and Storage Operations in Africa: Perspectives on Enhancing Grain Quality

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Abstract: Grain quality is largely driven by grain infrastructure (technology) and handling practices (application of knowledge on handling). The use of inappropriate infrastructure and inappropriate handling protocols poses food safety and health-related risks. This review provides evidence for the link between drying and storage operations in the context of preserving grain quality. The purpose of this study was to evaluate the close grain quality relationship between drying and storage, with an appraisal of operations in Africa. This study further benchmarked successful and scalable models in Africa to infer guidance for promotion of optimal and effective drying and storage initiatives. While open-sun drying is undoubtedly the most adopted approach to grain drying for the rural-poor farmers, this study revealed greater success in grain storage, especially with the breakthrough at the introduction and adoption of small-scale hermetic storage technologies. Upon assessment of the cob, WFP Zero Food Loss Initiative, and AflaSight models implemented in Rwanda and Uganda, this study suggests: (i) the adoption of system thinking; (ii) the use of sustainable approaches such as gender inclusion, sustainable financing options, and use of existing infrastructures along-side novel interventions; and (iii) enabling policies and political will as strategic pathways for successful implementation of improved grain-quality interventions during drying and storage. In the short term, grain handlers must develop appropriate grain management protocols during open-sun drying to limit the impact of drying-related grain quality deterioration. Consortia-based implementation of the three models evaluated in this review could improve grain quality, food security and safety, and market linkages with premium grain markets, fostering economic growth and transformation.

Keywords: sustainable grain quality; food safety; food security; system-based approach; Africa

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1. Introduction

The demand for high quality food products is on the increase globally [1]. In relation to grains, quality is broadly categorized into physical, compositional, and safety aspects [2]. Some of the safety grain quality attributes of great global concern include the presence of aflatoxins [3], residual chemical fragments [4], and animal remains that are a threat to human and animal health [5]. Compositional quality encompasses cooking, sensory, milling, viability, and the nutritional characteristics of grains. These directly influence the contribution of grains to food security. Physical quality attributes include moisture content (MC), bulk density, and several kernel properties such as size, hardness, density, and damage. Physical quality aspects relate to the economic and market value of the grains [6,7]. These quality attributes are largely driven by grain infrastructure (technology) and handling practices (application of knowledge on handling) among grain handlers. While developed countries generally maintain adequate infrastructure and grain handling practices to ensure hygienic processing and handling, the situation in developing countries presents notable disparities. Thus, the use of inappropriate infrastructure and infrastructure handling protocols poses a food safety risk associated with poor grain quality in developing countries where grains are a key ingredient in food security.

Grains are a major source of calories and protein, especially in developing countries, and thus their integrity must be protected. For instance, over 22% of the population in Africa consumes maize as its basic source of calories, making it the largest source of dietary calories on the continent [8]. In sub-Saharan Africa (SSA), 95% of maize is grown for human consumption [9], and thus the crop accounts for about 30% of the total energy intake rate of 52–450 g/person/day [10]. In Africa, maize, sorghum, rice, wheat, and millet are the major cereal grains. Additionally, common beans, chickpeas, cowpeas, pigeon peas, and groundnuts are the most cultivated legume grains [11,12]. The predominant crops, however, differ from nation to nation [13]. For instance, Nigeria is the largest producer of maize and rice in Africa [14]. Tanzania and South Africa are the closest competitors in maize production. Ethiopia is the largest wheat producer in Africa [15]. Other wheat producing countries include South Africa, Sudan, Kenya, Tanzania, Nigeria, Zimbabwe, and Zambia. Tanzania is the world's 7th and the leading producer of common beans in Africa [16]. Cowpea is majorly produced in West Africa. Globally and in Africa, Nigeria and Niger ranked as the first and second cowpea producers, respectively [17–20]. Despite the high grain production and consumption rates, Africa continues to suffer food insecurity and malnutrition [21,22]. Bjornlund et al. [23] posited that about 30% of the total population in SSA is food insecure. This could be associated with the high postharvest losses (PHLs)—both in quantity and quality that curtail the production efforts of several farmers [24,25]. A comprehensive review of the nature and magnitude of PHLs in SSA was provided through meta-analysis by Affognon et al. [26]. Grain loss in the SSA alone amounts to about USD 4 billion [27–29]. The PHLs of grains for Africa are estimated at 20% to 40%, which is particularly concerning given the region's low agricultural productivity [29]. These losses occur throughout the supply chain, from harvest through to consumption. The African Post-harvest Losses Information System (APHLIS) estimated grain losses, excluding consumption, at approximately 30% in 2022 [30]. When household consumption is factored in, the estimated PHLs in SSA decrease to about 5–13% for cereals and 12–18% for oilseeds and pulses [31,32]. Contributing factors to these high losses include a lack of knowledge, inadequate technology, and poor storage infrastructure, which are critical for effective post-harvest operations (PHOs) [27,33–37]. These issues emphasize the urgent need for improved practices and technologies to reduce PHLs and enhance food security in the region.

Grain PHLs include the food value lost from the harvesting of grains until their consumption [25]. Upon harvesting, grains undergo postharvest handling, including threshing, cleaning, drying, storage, processing, and transportation [29]. Whereas PHOs are primarily aimed at maintaining grain quality [38], grain quality losses in the form of inferior nutritional value, food-borne health hazards such as the presence of molds and mycotoxins, and economic losses when the produce misses market opportunity [25,39] may occur at each of the stages. The grain quality loss occurs due to several factors, including improper handling, bad weather conditions, and insect and mold infestations [29]. However, greater grain losses are observed during drying and storage operations, which require special attention to maintain the quality of grains [18,29]. About 15–25% of estimated total PHLs occur during storage [18], of which 10–15% is due to insect infestation and molding [1]. Reduction of PHLs is a fundamental component for sustainable agricultural productivity [40]. It also offers an alternative pathway for accessing food, alleviating poverty, and improving nutrition [26,41–43]. This emphasizes that storage is one of the value chain nodes with the greatest grain losses. Additionally, grain losses at storage could be overstretched by errors or ineffectiveness at the drying node along the value chain. It is thus important to evaluate the two value nodes (drying and storage) in tandem if robust grain handling strategies geared towards reducing PHLs are to yield positive results. This study sought to evaluate the close grain quality relationship between drying and storage with an appraisal of operations in Africa. The study further uses lessons from successful and scalable models in Africa to infer guidance for system-based approaches for promotion of optimal drying and storage initiatives.

2. Methodology

A narrative review approach was adopted in this study to establish the grain quality aspects surrounding drying and storage operations in Africa. A set of electronic search tools were used to establish relevant peer-reviewed literature, including Science Direct, PubMed, Google Scholar, and Web of Science. A preliminary assessment of the abstract was conducted for each literature piece obtained to ascertain its alignment with the objectives of the review. Other relevant articles were retrieved through evaluating reference lists and tracking the articles through Google Scholar. Some of the keywords included 'grains OR seeds AND quality OR food safety', 'grains OR seeds AND postharvest operation AND Africa', 'grain OR seeds AND drying OR storage AND Africa, 'traditional grain drying AND Africa OR Sub-Saharan Africa'. The review considered papers that provide information on the traditional and improved drying and storage technologies used in Africa—characteristics, practices, pros, and cons, with emphasis on grain quality. The review also incorporated personal observations and anecdotal evidence, which enriched the analysis by providing practical insights into the challenges and practices observed in grain drying and storage in Africa. These firsthand accounts complemented the data from existing studies and reports, offering a more nuanced understanding of the issues at hand. This combination of empirical data and personal experience helped to highlight the real-world implications of post-harvest losses and the effectiveness of various interventions in different contexts. The study further evaluated three successful and scalable postharvest models in Africa to draw lessons for enhanced drying and storage technology adoption on the continent. The models were selected based on approach and impact in line with grain quality and food security. Only models involving drying and storage were prioritized. Some of the thematic areas included drying, storage, postharvest handling in Africa, grain quality, and technology transfer. The overall research strategy for the whole article analysis and outcomes is presented in Figure 1.

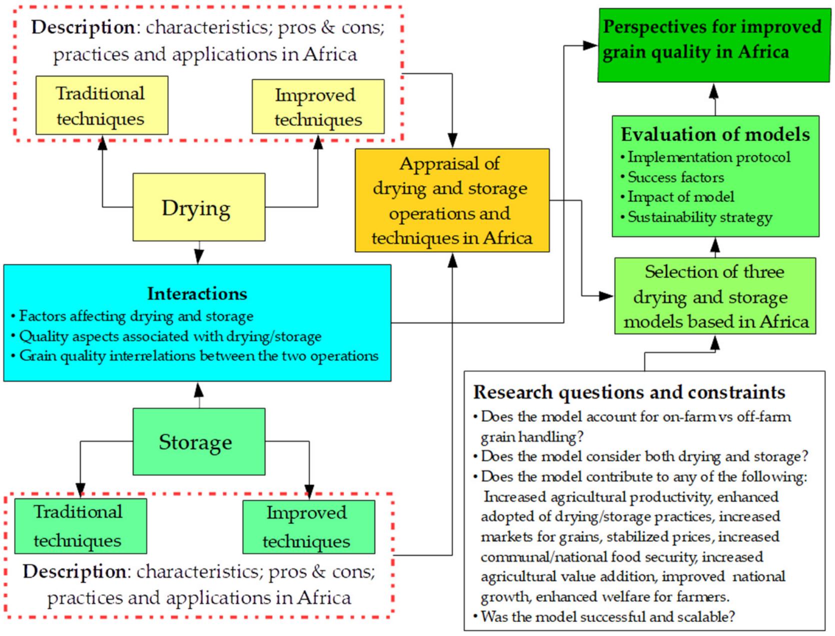


Figure 1. An overview of the research strategy.

3. The Nexus between Drying and Storage: A Tale of Grain Quality

Drying usually precedes storage in the grain value chain. It influences shelf life and reduces grain losses during storage and is one of the most important PHOs [42,44]. On the other hand, storage is a temporary and recurrent step throughout the logistics and handling of grains from producers to processors and their products from processors to consumers [45]. Grain storage serves two purposes: (i) it enhances marketing efficiency by ensuring grain continuous and/or phased grain supply in extreme events such as bumper harvests, eventually stabilizing prices [27,46], and (ii) it facilitates food availability, thus fostering food security [47,48]. Effective storage, however, is one that maintains grain quality to facilitate a year-round supply of grains [27,46,49].

It is worth noting that all grain quality errors made during drying contribute to the cumulative grain quality losses during storage, as shown in Figure 2. Drying is a heat and mass transfer process triggered by water vapor pressure differences between the food material and the environment [38,42,50,51]. The drying process depends on temperature, initial MC, drying time, and airflow, although the magnitude of their influence varies by drying system. Storage, however, depends on temperature and aeration (interaction with the external environment). Drying is therefore associated with a variety of rate processes, such as physical, chemical, or biological transformations, which in turn may result in desired or unwanted changes in the product quality, such as shrinkage, color change, texture change, flavor, or other attributes of the grain product. In the context of drying, it has been reported that prolonged exposure to high drying temperatures results in grain weight loss, loss of important nutrients [52], increase in breakage susceptibility, affects grain color, and loss of grain germination potential [53], as summarized in Figure 2. Odjo et al. [54] found that drying at high temperature modified the color and denatured the salt-soluble proteins of corn kernel. Higher breakage susceptibility was found with paddy dried at high temperatures [55]. Airflow affects the final MC of the grains as relatively high air flow rates are associated with uniform drying. Inadequate drying of grains with high initial MC results in the growth of molds within the drying system. Temperature and aeration interactively facilitate loss of grain quality during storage. Favorable temperatures coupled with aeration of the storage system allow growth and multiplication of insects and molds during storage. Insect infestation results in grain physio-chemical quality losses in the form of weight loss and nutrient degradation [56,57]. Molding to a smaller extent may reduce the grain germination potential [58].

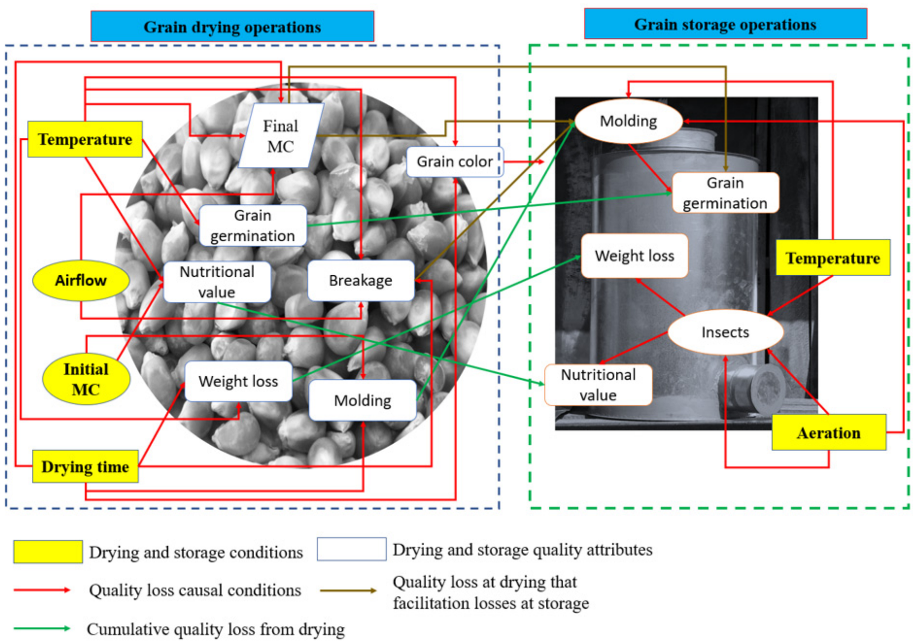


Figure 2. The relationship between drying and storage operations.

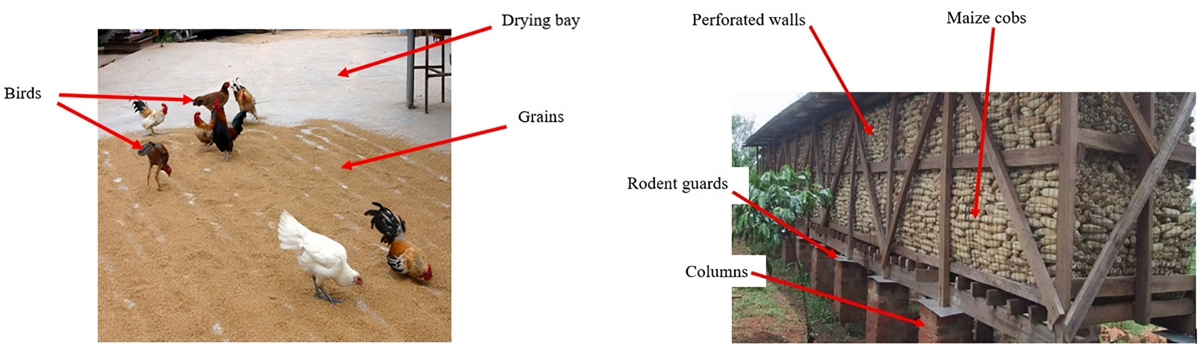
As emphasized before, the grain quality losses at storage could be fueled by the drying losses. Some of the pertinent quality attributes of the drying system responsible for accelerated quality loss during storage include final MC and breakage (Figure 2). The heat stress during drying can cause fissures, cracks, or even breakage, important grain quality indices that contribute to losses during storage [38]. Grain breakage due to excessive drying allows storage fungi and rots to quickly proliferate under favorable moisture and temperature conditions [59]. Storage temperature and grain MC impact storage unit respiratory and microbiological activity, thus influencing grain quality [49,52]. For instance, high storage temperatures and grain MC (under-dried grains) accelerate grain biological activity, leading to the deterioration of grains. Typically, grains are dried from the harvest MC of about 17% to about 12–13% recommended for safe grain storage in the tropics [1,33,60–63]. Grains stored at MC of 12–13% are less susceptible to microbial growth and associated with very low enzymatic activity and grain tissue respiration, which prevents sprouting and germination during storage [43,49,60,64], eventually offsetting the qualitative losses at storage. Molding, weight loss, loss of nutritive value, and loss of germination index during drying certainly contribute to the cumulative storage grain quality losses. Grain color loss due to inappropriate drying, if not checked, could be carried on to the storage systems, further accounting for the losses at storage. In summary, this section justifies the need to monitor drying and storage operations as a subsystem rather than individual nodes within the grain value chain.

4. Grain Drying Operations in Africa

4.1. Conventional Drying Technologies

4.1.1. Open Sun Drying

Conventional drying using open-sun drying has been practiced for decades [42,50]. Open-sun drying is by far the most widely used grain drying method in Africa, due to its simplicity and low cost [33,42,43,65]. The tropical climatic nature of Africa with distinct dry and wet seasons explains the continued dependence on open sun drying even with the development of more efficient technologies. In open-sun drying, the grains are spread out in thin layers either on bare ground or on tarpaulins (Figure 3a) for efficient exposure to solar radiation [61]. The sun offers a readily available free source of heat energy that is required to dry grains to acceptable MC, an advantage over some other technologies that require additional resources to facilitate heat generation. Also with this approach, farmers can actually dry their produce in available spaces near their homes or along roadsides [63]. Despite the simplicity, open-sun drying is characterized by drudgery in the form of labor and time and an inability to control the drying process [66–68]. Additionally, the crop is exposed to bad weather, atmospheric dust, intrusion by animals, birds, insects, pests, and rodents [43,51,69]. Operators (usually children and women) often move their feet over the grain while mixing and collecting at the end of the drying period, creating a less than desired sanitary condition for the grains.



(**a**) (**b**)

Figure 3. (**a**) Birds feasting on the grains exposed to solar irradiation for drying; (**b**) unthreshed maize cobs loaded into the crib. Modified from Asea et al. [70].

4.1.2. Traditional Cribs

The cribs, also commonly referred to as maize cribs, are used interchangeably for drying and storage, although they are primarily used for drying of early-harvested maize cobs. Presently, there is a shift to extend its use to include many other crops. The crib structure is characterized by (i) a rectangular-shaped structure with perforated walls made of straw, palm leaves, bamboo, or wire netting; (ii) raised off the ground (about 0.5 m); (iii) the length is aligned perpendicular to the flow of wind; and (iv) has rat guards on the columns to prevent rodents (Figure 3b) [39]. The cribs are easy and cheap to make compared to storage bins. Maize with husk is protected well for 3–6 months [46]. The grains are, however, exposed to the varying weather conditions, thus hampering the drying process. In wet (very humid) and dry (less humid) seasons, maize's hygroscopic characteristics allow it to absorb and release moisture, respectively. This continuous loss and gain of moisture might result in crack formation or even breakage. Cribs are common in southwestern and eastern Nigeria [39].

4.2. Improved Drying Technologies

4.2.1. Use of Solar Dryers

Despite the shift from traditional open-sun drying, farmers in Africa continue to harness the energy from the abundant solar radiation. This is possible with solar-based drying technologies commonly called solar dryers. Solar dryers have been widely adopted as an alternative to open-sun drying [60,64]. Solar dryers differ from open-sun drying in that they provide enclosure to the drying material, thus promoting better product quality [61]. Solar dryers are classified based on the nature of air flow (active and passive dryers based on forced and natural convective air flow, respectively) and mode of heat transfer (direct or indirect heat transfer) [43,71,72], and hybrid solar dryers (based on multiple energy sources). Nonetheless, most dryers are a combination, such as direct passive and indirect passive solar dryers, as observed in Table 1. Compared to other improved drying techniques, solar drying is the most preferred food processing technology in Africa, probably because of reduced energy requirements, low cost, and affordability, factors that favor resource-constrained communities [64].

Table 1. Solar drying technologies used in Africa.

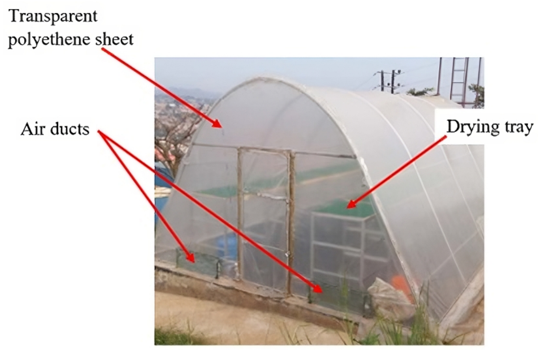
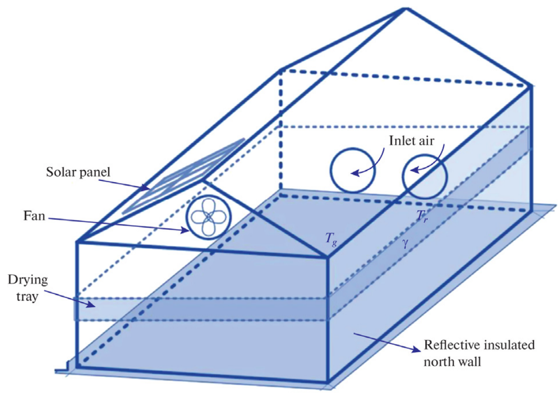
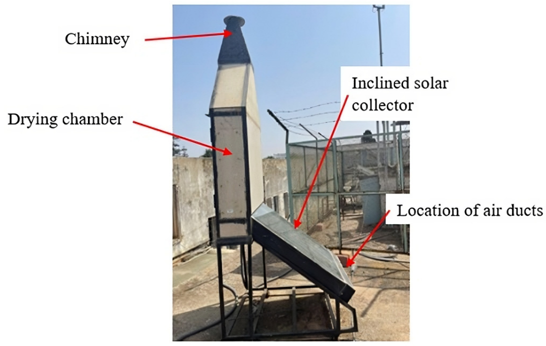
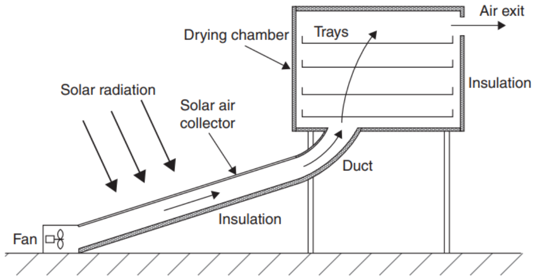
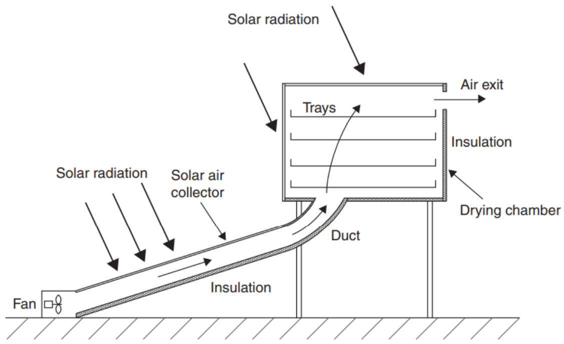
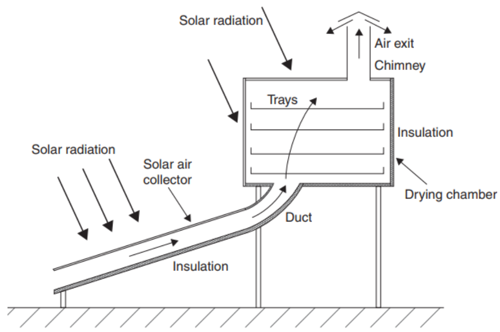
Drying Technology	Characteristic Features and Functionality	Classification	Pictorial
Direct solar dryers [61,73,74]	The drying chamber consists of drying trays enclosed in a transparent cover made of polyethene with air ducts to maintain air circulation in the system. Can be of box or greenhouse type depending on the production capacity. The air circulation can be due to natural convection (passive) or forced convection (active mode)	Direct passive solar dryer (greenhouse type)	
		Direct active solar dryer (greenhouse type)	

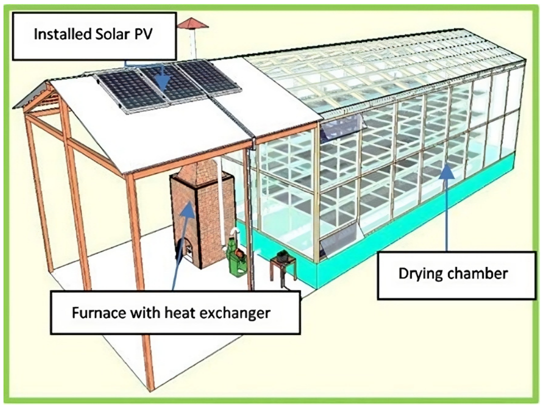
Table 1. *Cont.*

Drying Technology	Characteristic Features and Functionality	Classification	Pictorial
Indirect solar dryers [75,76]	Composed of three critical parts—the solar collector, drying unit, and an air duct for circulation. The drying chamber is embedded with drying trays on which grains are placed and a chimney to allow the humid air to exit. The air ducts transport hot air into the drying chamber and over/through the drying trays after first passing through a low-pressure drop solar collector. The solar collector is normally inclined for maximum solar absorption. Can operate at higher drying temperatures, thus facilitating deep layer drying	Indirect passive solar dryer	
		Indirect active solar dryer	
Mixed mode solar dryers [76,77]	Consists of the solar collector, drying unit, and an air duct for circulation. The drying unit consists of drying trays enclosed in a transparent cover made of polyethene. The air ducts maintain air circulation in the system. Collects solar radiation from the drying chamber and the solar collector, which are features specific to the direct and indirect solar dryers, respectively. Can be in the form of passive (without fans) and active dryers (with fans)	Active mixed mode solar drier	
		Passive mixed mode solar drier	

Passive solar dryers operate based on the thermosyphon effect. Here, the solar-heated air is circulated through the crop by either buoyant forces or because of air pressure or a combination of both. Air circulation within the system is by natural convection. In active solar dryers, air circulation is maintained with forced convection generated using fans that are powered by either a grid or solar photovoltaic module. Passive solar dryers are simple and relatively cheap compared to active dryers. Active dryers are adequate for high-moisture crops, although effective control of air velocity is required for optimal drying [43,51]. Passive and active modes can be applied to both direct and indirect solar dryers, as shown in Table 1.

Direct and indirect solar dryers differ in heat transfer to the drying material. For direct solar dryers, solar radiation is directed to the drying materials, while only heated air reaches the drying materials under the indirect solar system [78]. With direct solar dryers, the solar radiation is transmitted into the cabinet and absorbed while being partially reflected to the atmosphere during drying. Some direct dryers, such as the box type, are embedded with a black metallic sheet at the base to enhance capture of solar energy [77]. Direct solar dryers operate on the principle of the greenhouse effect, where thermal energy accumulates in the drying chamber [75,78,79]. This facilitates grain temperature rise, hence enabling moisture loss. The moisture is then carried away by the less humid air coming in through the inlet air ducts to the outside through the outlet chute [51]. Direct solar dryers can operate in passive and active modes, as described in Table 1. The latest novel development in grain drying in Africa is the Dehytray™ (Figure 4a) developed at Purdue University that operates on the principles of direct solar dryer. It has been tested with maize in Kenya and Senegal [69].

(**a**)



(**b**)

Figure 4. (**a**) The Dehytray™ dryer (JUA Technologies International, West Lafayette, Indiana, USA) [80]; (**b**) Solar biomass hybrid dryer with both the direct solar drying system and the furnace for biomass combustion [53].

For indirect solar dryers, the solar radiation is not directed to the drying product but rather heats the air in the solar collector. The heated air then flows into the drying chamber and over/through the drying trays, picking up moisture from the crop. The moist air is discharged through air vents or a chimney at the top of the chamber [43,51]. Drying takes place due to the difference in moisture concentration between the drying air and the air in the vicinity of the crop surface [62]. They offer better control over drying as well as good quality products compared to direct solar dryers. They present low chances of heat damage as the crop is not directly exposed to solar radiation [51,62]. Indirect solar dryers can operate in passive and active modes, as described in Table 1.

Mixed-mode solar dryers operate on the combined effect of the direct and indirect solar dryer principles [51,78]. Thermal energy is collected directly in the drying chamber. Also, the drying front is enhanced by the preheated air coming from the solar collector. The food product in the mixed-mode dryer is heated by both a transparent drying chamber and the heated air column from the solar collector, thus enhancing the drying process [77]. The air circulation from the solar collector occurs under natural and forced convections in passive and active mixed-mode solar dryers, respectively (Table 1) [61]. The fans in the active mixed-mode solar dryer are powered using either an AC power grid or DC sourced from solar photovoltaic (PV) modules. Mixed-mode dryers are applicable where faster drying is required [51]. In hybrid dryers, an auxiliary energy source is used to back up the pre-heated air in events of bad weather. Auxiliary energy could be derived from on-grid electricity, liquefied petroleum gas (LPG), diesel, or biomass (Figure 4b). The integration of these energy sources can lead to a reduction in drying time and have positive effects on the quality of the product [53].

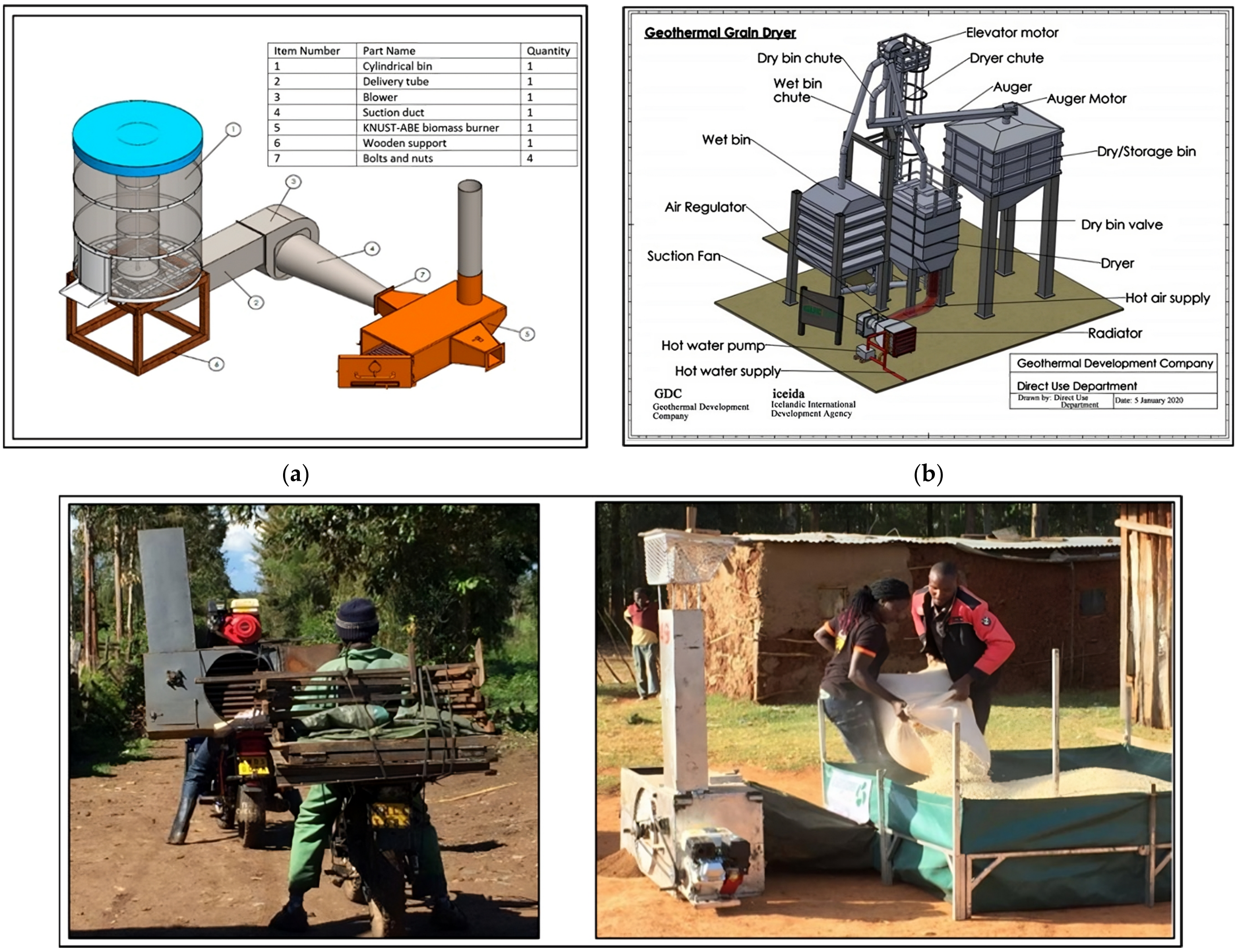
4.2.2. Use of Mechanical Dryers

Mechanical dryers have been deployed in many African nations at large-scale production and processing sites. The deployment of mechanical dryers for large-scale production could be attributed to the large capacity and efficiency of the systems, with little chance of drying failure as they are not weather-dependent. Steam, electricity, gas, and fossil fuels are the main sources of energy with large-scale mechanical dryers. However, the energy requirements for these drying techniques are significant, and the cost of both securing and using them is high [81]. For most developing nations experiencing electrical power challenges, this high power demand makes the technologies less dependable and adaptable. Therefore, small-scale farmers in Africa continue to adopt the conventional method of drying, which lowers the grain quality. Nonetheless, several research efforts are underway to ensure small-scale farmers and processors benefit from the quality attributes that come with mechanical dryers, although commercialization is still low given the high energy costs associated with the mechanical dryers. Some of the mechanical dryers include the crossflow column maize dryers developed in Ghana, the geothermal grain dyer developed in Kenya, and the EasyDry M500 maize dyer developed by AflaSTOP as an open source technology in Kenya.

The crossflow column maize dryer consists of three main parts: a cylindrical drying bin, a portable biomass burner, and a fan (blower) (Figure 5a) [82]. The dryer was developed at the Department of Agricultural and Biosystems Engineering, Kwame Nkrumah University of Science and Technology (KNUST). The mobile dryer is powered using biomass (corn cobs, wood chippings, and rice husk) at an estimated biomass feed rate of 12 kg/h (based on corn cobs) and has a drying capacity of 500 kg/batch. During operation, the biomass burner supplies heat to the drying system through the heat exchangers. The grate just below the burner allows the free fall of the ash after combustion, thus facilitating easy collection. The blower pulls air from the biomass burner through the heat exchangers and then forces the drying air through an air delivery tube to the drying bin. At the dryer's plenum, drying air is forced to pass through the drying chamber radially by restricting the movement of the drying air in the plenum by using a stopper.

The geothermal grain dryer (Figure 5b) derives the drying energy from geothermal fluids derived from Menengai well 3 or 12 located at Menengai Geothermal Development Company station, facilitated by heat exchanger counter-current flow mechanisms with fresh water [83,84]. The batch type dryer consists of four compartments with evenly spaced fins to guide the air flow through the drying chamber. The suction pump blows ambient air through the hot water tubing to the dryer. The supplied hot air enters the grain buffer section in the dryer through evenly spaced openings across the four compartments. The elevator loads the wet grains into the dryer through the dryer chute. Upon attaining the desired MC, the dried grains are loaded into the storage bin. The inclusion of filleted flow guides results in a relatively uniform velocity, temperature, and turbulence kinetic energy distribution across the dryer [83]. This dryer presents an alternative grain drying option for industrial operation, as the use of geothermal energy is relatively cheaper compared to conventional fossil fuels and electricity [83].

The EasyDry M500 portable biomass maize dryer was developed by AflaSTOP in Kenya [48]. The dryer uses biomass, in the form of maize cobs, as an energy source. The heat and smoke produced by burning biomass material are passed through the heat exchanger and finally out through the chimney. The clean air under forced convection passes over the heat exchangers, where it picks up the heat required for the drying process. The dry, hot air is then pushed through the maize bed, which is suspended on a 'table'-like structure, placed within a canvass 'bag' (Figure 5c). The dryer capacity is estimated to be 1.5 MT/day, reducing maize moisture content from approximately 17% to 13.5% [68,85]. The EasyDry M500 dryer is easy to assemble and disassemble to facilitate transfer from one farmer to another using common motor bikes. It is fast yet less laborious compared to conventional drying systems. The dryer has a roof to protect the grains from adverse weather conditions.



(**a**) (**b**) (**c**)

Figure 5. Small-scale mechanical drying technologies developed in Africa: (**a**) Crossflow column dryer developed by KNUST [82]; (**b**) Geothermal grain dryer developed in Kenya [83]; (**c**) EasyDry M500 dryer developed in Kenya [85].

5. Grain Storage Operations in Africa

Africa continues to enjoy the benefits of grain storage, including stabilization of prices and ensuring food availability. Grain storage in Africa is broadly classified into traditional and improved technologies [39], as discussed in this section.

5.1. Traditional Grain Storage Facilities

The traditional grain storage approaches are decades old, but their use for grain has been sustained for generations [46]. The developing nature of many African states continues to frame the use of traditional storage facilities as relevant, even in the face of criticism relating to their potential to maintain grain quality. Traditional grain storage at the farm and domestic level includes open aerial storage, open fireplaces, African gourds and granaries, jute, and polythene bags [39].

5.1.1. Open Aerial Storage

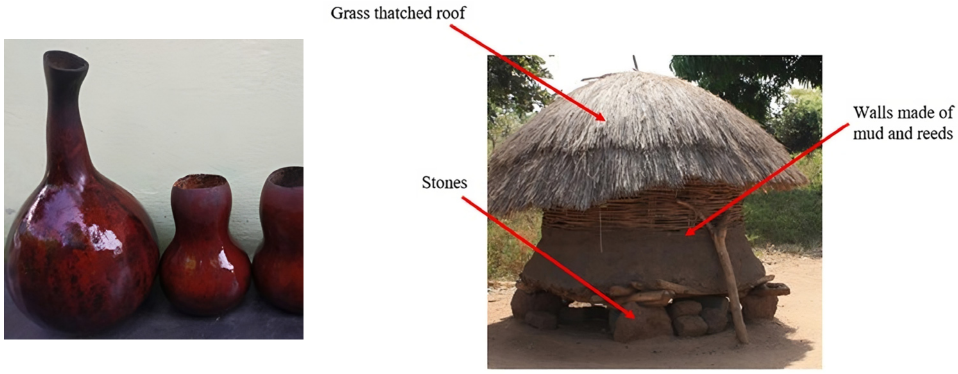
With the open aerial storage, the unshelled cereals are suspended in bunches using rope or plant material, under eaves, from the branches of trees or the top poles driven into the ground [39,46]. Precautionary measures are taken while utilizing the approach to guarantee that grain in storage is protected from adverse weather conditions. The grain remains in the air and the sun until the farmer needs it for consumption or marketing. Popular storage locations include under the roof of homes, hanging from the roof beams, and spreading out on a grid in the ceiling, where high temperatures due to direct solar radiation heat up the grains to reduce the moisture content and may also kill the developing larvae in the seeds, thus preventing insect infestation [46].

5.1.2. Open Fire Storage

Smoking has proved an important preservation method for many foods. The open fireplace storage benefits from the same approach. In this method, the grains are stored near the heat and smoke of the burning firewood, which penetrates the grains to keep them free from insects and pest attack [48,86]. In rural communities, farmers usually store grain crops in the kitchen hut, where they can then benefit from the raising smoke coming off the cooking stove.

5.1.3. African Gourds

The African gourd (Figure 6a) is an indispensable element of the African heritage. It could be the reason many Africans from ancient days associated it with their day-to-day operations, including the storage of food items. Gourds, a dried form of fruit from the *Cucurbitaceae* family, are quite common in the tropics and subtropics. The outer surface of the gourds is varnished or oiled. Upon filling with the grains, it is sealed with a lid to ensure an airtight condition. Gourds are used for storing small quantities of food grains (5–30 kg) required for home consumption or planting for a duration of six months to one year [46]. Gourds are normally kept indoors and on raised platforms to lessen the effects of moisture absorption and insect infestation.



(**a**) (**b**)

Figure 6. (**a**) Well varnished African gourd for small-scale grain storage [46]; (**b**) A structure of the traditional granary used for grain storage in Africa [87].

5.1.4. Granaries

From way back, an African home with a granary was considered food secure, an indication of its great significance to the African heritage. However, the rise of modern technologies pushed the use of the traditional African granaries (Figure 6b) to near extinction. In some communities, granaries are still existent and used for the storage of grains. The use of traditional granaries among farmers despite their low capital investment could be attributed to their limited knowledge of their construction and their susceptibility to fire damage [88]. Granaries are made of local and inexpensive materials such as grass, wooden poles, and clay, although they become dilapidated over time [48]. They are elevated from the ground and fitted with rat guards. The walls are often made of mud and reeds with a relatively smooth lining.

5.1.5. Storage Bags

Farms, villages, and commercial storage centers often use sacks in sizes ranging from 25 to 100 kg for short-term grain storage [37,89]. Presently, polypropylene bags are becoming common compared to the other woven jute and sisal sacks that were previously used for grain storage. For instance, more than 73% of farming households use woven polypropylene (PP) bags for grain storage in Uganda [90]. Storage bags are very convenient while in use, as they require less space than granaries since they can be piled in storage or folded away when not in use. However, storage bags have a limited life span of less than 2 years, after which they become less efficient for storage. They are also very susceptible to punches [88]. The non-hermetic nature of the sacks, however, allows the grain to interact with the environment, thus exposing the grain to pest growth due to the availability of oxygen. The bags are often placed on bare ground during storage, exposing the grain to moisture absorption during storage.

5.2. Improved Grain Storage

5.2.1. Grain Treatment with Pesticides

Pest repellants have been in grain storage systems for years in Africa. Previously, natural pest repellants such as pepper were used. The use of pesticides has escalated with the high invasion of grain storage pests. Several synthetic repellants are used along with conventional storage methods such as granaries, warehouses, and storage bags to lessen the impact of the grain damage by insects, pests, rodents, and mold [18,89,91]. Here, the chemical repellants are mixed with the grain by hand before storing it. These additives and chemicals create an unpleasant atmosphere for insects and pests to coexist in the grain ecosystem, but sometimes affect the sensory properties of grains. The increased exposure to chemicals during application further increases the risk of cancerous illnesses among humans, as there is no convincing approach used to remove the chemicals prior to grain consumption.

5.2.2. Community Storage Structures

Community storage structures are permanent structures (Figure 7a) that are communally owned and managed for grain storage. They are operated under the cooperative or farmer groups model since they require huge capital investment [39]. The communal storage structures are always centrally located within the proximity of grain production [92]. In these stores, grains are either poured directly on a well-plastered floor or stacked in polyethene bags. Synthetic pest repellants are applied to grains to reinforce the storage efficiency of the community structure.

(**a**) (**b**) (**c**)

Figure 7. (**a**) A traditional warehouse for grain storage [39]; (**b**) Storage bags stacked on pallets; (**c**) Bin storage silo in South Africa [39].

5.2.3. Use of Warehouses

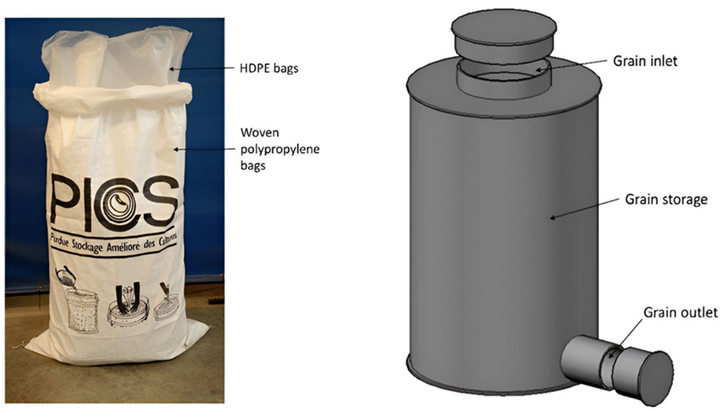
Warehouses and community storage structures are quite interrelated in terms of operation. However, warehouses are either state-managed storage facilities or privately managed by well-established companies. Although they have the same physical structure, warehouses are more equipped with facilities for effective grain storage, such as rodent baits/traps and pallets (Figure 7b). Well-established warehouses employ the principle of cover and plinth (CAP), where the grain bags are stacked on pallets and covered with either polyethene material or tarpaulin [18]. Nonetheless, grain storage is often compromised because of the continuous grain-environmental interaction. Despite the cost of investment, farmers acknowledge the role of warehousing in the management of PHOs. Reportedly, 78% of maize traders in Ghana indicated the need for a warehouse in the marketplace for maize storage purposes [35].

5.2.4. Bin Storage Silos

Grain handling companies use bin storage silos for bulk grain storage as they take up less space and can be handled mechanically, decreasing bagging and handling costs. Bin storage silos are elevated cylindrical metallic structures made of zinc-plated galvanized steel sheets. The bin storage silos are erected on a circular reinforced concrete floor [93] (Figure 7c). The zinc plating reduces the chances of corrosion [94]. Bin storage silos have been adopted by most of the largest grain-producing countries in Africa, such as South Africa, with over 100 grain silos across the country [39]. However, they require high initial investments. The system equally requires continuous aeration to control grain temperatures and reduce moisture migration and condensation near the top of the grain pile, thus increasing operation costs.

5.2.5. The Novel Hermetic Storage Technology (HST)

The novel hermetic storage technology (HST) provides an alternative to the conventional storage methods. HST works on the principle of respiratory effects characterized by very low oxygen and high carbon dioxide within the storage unit [89,95]. Oxygen reduction is partly due to internal oxygen use by the insects themselves, the oxidation of the product, and fungal growth. The low permeability envelope maintains a constant moisture environment [89,96]. Several HST have been approved for commercial use in Africa, including Purdue Improved Crop Storage (PICS) bags (Figure 8a), SuperGrainbags, ZeroFly bags, Elite Storage Bags, AgroZ Storage Bags, plastic silos, and metal silos (Figure 8b), among others [11,89,97,98]. Hermetic bags require relatively low capital investment, suiting smallholder farmers' capabilities [89]. HSTs do not require any application of chemicals, as the case is for other storage methods.



(**a**) (**b**)

Figure 8. (**a**) Triple bagging mechanism of the PICS bag consisting of HDPE bags and woven polypropylene bags; (**b**) The structure of metal silo indicating the inlet and outlet [18].

6. Appraisal of the Drying and Storage Operations in Africa: The State of Grain Quality

6.1. Assessment of Drying Operations

6.1.1. Traditional Drying Techniques

The conventional open sun and crib drying expose the grain to unfavorable and unprecedented weather patterns. When grain harvesting coincides with unfavorable drying weather conditions, such as the rainy season, the drying process can take up to 5 days [82,99], causing production delays. The uncontrolled drying condition may result in uneven drying of grain [64], which eventually results in grain quality deterioration. Uneven drying may facilitate mold development during subsequent storage, thus exposing humans to cancerous diseases [33,42,43,63,100], promoting poor growth and development among infants and children [101], and affecting the quality of several animal products if the grain is fed to animals. This is not surprising, as grains from Africa have been widely linked to high levels of mycotoxins, especially aflatoxins. For instance, Ayalew [102] reported that 88% of maize grain sampled in Ethiopia had aflatoxins. According to Nji et al. [103], the mycotoxin contamination rate for maize ranges between 50–100%, with Togo at 100% contamination. This eventually constraints the market potential for African grain, especially in premium markets such as the European Union, where aflatoxins contamination is critically monitored [33,103]. Also, the grain handling approach used in open-sun drying, where operators trample on the grain while mixing and collecting at the end of the drying period, contamination from birds and other animals that continue to feast on the grains may lead to food borne diseases among humans [5].

Uneven drying could also influence the milling quality, especially with rice. Mill recovery and whole grain level are identified as key quality parameters that determine the profitability of rice businesses in Uganda [104,105]. Open-sun drying has been linked to an increased broken rice percentage, thus reducing rice quality. This could be attributed to the long drying time under high-intensity sunlight [105,106]. Parboiling has been promoted among rice growers in some parts of Africa as an alternative pre-treatment method to improve the milling yield. For example, over 90% of harvested paddy in Nigeria is processed as parboiled milled rice before marketing [106]. Parboiling is a hydrothermal paddy treatment where paddy is soaked in hot water and steamed prior to drying and milling. The process loosens the hull, thus improving the milling process. Withstanding, the farmers continue to use the open sun drying for parboiled rice, exposing it to dust and stones.

The structure of the crib allows flow of oxygen within the drying chamber, thus creating a favorable environment for the growth of insect pests. This is exacerbated by the favorable temperature created through heat generation due to maize cob stacking. Temperature is one of the key environmental factors affecting the physiological, life history, behavioral, and population processes of arthropods [107]. There is also potential for the transfer of insect pests with the cobs from the field to the drying unit, facilitating rapid growth and development of the insect population [108]. Insect infestation promotes higher grain insect damage, thus affecting physical quality parameters such as weight, bulk density, and kernel density. The relative increase in grain temperature may promote physio–chemical grain deterioration in sensory properties such as color. Grain color is used to infer grain quality and define the consumer preference, especially in rice, beans, and maize [109]. A general decrease in the maize grain yellowness was observed with an increase in temperature during the storage study by Paraginski et al. [109]. The hygroscopic characteristics of grains that allow continuous absorption and loss of moisture may result in breakage as the grains are exposed to varying weather conditions under the traditional crib.

6.1.2. Improved Drying Techniques

It is observed that grain drying with the improved drying systems is done under a controlled environment. For instance, the grains are placed in the drying chamber with all solar dryers as opposed to open tarpaulins to the open sun drying. This reduces the exposure of grain to contamination from dust and other animals and enhances grain quality.

There is a tendency to overheat with passive solar drying, especially when effective air circulation is not achieved [67]. Overheating is associated with the loss of valuable vitamins and proteins, thus reducing the product quality [110]. Additionally, the ineffective moisture removal from the drying chamber in direct passive solar drying due to poor design may result in accumulation of moisture (high humid zones) within the drying chamber, thus facilitation of rewetting of grains and high heat concentration zones within the grains mass, causing eventual breakage susceptibility. To the contrary, indirect passive drying reduces grain cracking and aids in maintaining vitamins and color [51,61,71], therefore maintaining grain quality. Higher drying rates observed in the active and mixed-mode solar dryers are mainly attributed to the high air flow rates due to forced convection. Higher air velocity enhances the uniformity of particle size and grain quality, although excessively high velocities increase the grain shrinkage rate, therefore affecting grain quality [111]. The high drying rate also reduces the exposure of grains to drying temperatures, thus facilitating the retention of vital vitamins and proteins [54]. Despite the better performance compared to open-sun drying, solar dryers are weather-dependent. Solar drying systems such as passive types associated with low drying rates are prone to failure due to weather uncertainties. In bad weather, the chances of uneven drying are high, delivering grains of varying MC and hampering grain quality. This could culminate in molding of the grains both during drying and storage.

Most of the industrial-scale mechanical dryers are automated with limited human interaction. This eventually reduces contamination during operation. Additionally, the automation improves the monitoring of machine drying conditions (temperature, airflow, and moisture removal), thus guaranteeing grain quality [112]. Nonetheless, small-scale mechanical dryers developed through different research across the continent promote the production of high-quality grains. For instance, the use of heat exchanger mechanisms in the crossflow column dryer, the geothermal dryer, and the EasyDry M500 allows for the use of clean heated air for drying, as opposed to the heat mixed with soot produced by the burners. A study by Obeng-Akrofi et al. [82] revealed that the crossflow column dryer maintains the drying air temperatures across all drying levels, thus facilitating even grain drying. The dryer was found to have an average drying temperature of 38.5 °C, which is good enough to maintain seed viability and reduce breakage susceptibility (the maximum drying temperature for seed viability and consumption is 55 °C and 90 °C, respectively) [68]. Additionally, even drying enables the production of grains of relatively uniform physical quality in terms of MC, kernel size, and bulk density. The drying time for the EasyDry M500 was found to be 3 h, which is faster compared to the 10 h observed with the traditional open-air drying in the same study [9]. Additionally, the chances of moisture condensation are very low as the dryers are fitted with fans to boost air velocity, reducing the risk of mold development.

6.2. Assessment of Storage Operations

6.2.1. Traditional Storage Techniques

Traditional grain storage, such as open aerial storage, open fireplaces, African gourds and granaries, jute, and polythene bags, is a cheap and convenient approach for many farmers but comes with severe grain quality losses [113,114]. Aerial storage exposes the grains to erratic environmental humidity conditions, thus making the grains susceptible to molding. Open fire storage is relatively effective at protecting grain from insects and other pests' infestation due to the toxic effects of the smoke [115], although the grains are subject to contamination due to the soot that comes with the smoke. Yadav and Tiwari [116] found that exposure of wheat seeds under storage to smoke resulted in more than 50% insect mortality after 72 h. Soot may, in turn, influence the grain color changes during storage. Additionally, smoke could potentially influence the sensory attributes for the grain kernels and eventually its market and post-processing potential. Saka et al. [117] investigated the effect of smoking on the nutritional composition of maize flours and the sensory attributes of maize porridge in Malawi. Sensory analysis was done with a 12-member trained panel and followed by acceptability studies among school-going children and mothers. The study revealed that smoking had no significant effect on proteins, fats, zinc, or iron in comparison to traditional dried maize, except for the higher amounts of ash and iron. The acceptability of porridge among the mothers was highly influenced by the unique smoky flavor. There was no significant difference in the acceptability of porridge among children.

It is hypothesized that smoke improves seed viability, germination percentage, and stimulates seeding vigor as it contains bioactive compounds called butanolide responsible for regulating the germination [118]. A study by Modi and Bornman [86] revealed that seeds stored using the open-fire method showed higher germination and vigor than non-smoked seeds. In the same study, the smoking approach was more efficient in moisture reduction compared to the non-smoking method. Iqbal et al. [119] investigated the effect of plant-derived smoke on wheat seed germination and post-germination growth stages. The study finding indicates that wheat seeds treated with plant-derived smoke had a significant increase in germination percentage, germination index, and seeding vigor, root, and shoot growth compared to untreated seed. Similar observations were made by Yadav and Tiwari [116] for germination percentage, germination index, the seeding vigor with wheat. However, over exposure of seed to smoke may have inhibitory characteristics to seed germination. In a study by Yadav and Tiwari (2018), the germination percentage was 100% after 1, 6, and 12 h of exposure, 96% after 24 and 48 h of exposure, and 94% after 72, 96, and 120 h of exposure to smoke. The study, however, did not evaluate whether the exposure time significantly affected the germination percentage.

African gourds provide a hard surface that reduces the permeability of moisture between the environment and the grains, eventually reducing the possibility of molding during storage. The hard surface further provides good grain protection against pest invasions that could affect the grain's physical characteristics. Granaries have rat guards that prevent rodents' attacks. This in turn enhances grain quality as the grains will be free from rodent excreta. Also, their elevation from the ground provides a much safer environment for grain storage as it reduces the chances of water absorption by the ground that could result in molding. However, the nature of the materials used in the construction does not guarantee hygienic handling of food, thus compromising grain quality. Lack of adherence to best practices is another grain quality challenge when using granaries. Farmers often do not clean out the old grain from granaries prior to restocking. This facilitates the transfer of pest infestation from old grain to newly harvested grain, thereby promoting grain kernel damage, which eventually affects the physical grain quality [88].

Storage bags are highly susceptible to rodent attack given their soft lining. Thus, the grains are often mixed with rodent excreta. Also, the non-hermeticity of the storage bags creates a favorable environment for insects and pest infestation. Heavy insect infestation is linked to loss of stored grain weight, causing nutritional, grain germination potential, and commercial loss [56]. Insects damage the grain germ, thus affecting the grain germination potential. Melese et al. [120] found that woven polypropylene (PP) bags had the least germination of 72.5% compared to PIC bags and GrainPro bags at 80.5% and 87%, respectively, after 9 months of storage without any treatments. In a study by Dijkink et al. [89], it was observed that grain damage after storing in storage bags for over 200 days (about 6 and a half months) was so great that the grain of all the maize was rendered of an unmarketable quality. Additionally, high moisture grain storage in woven PP storage bags is prone to molding as they present limited air circulation compared to the jute bags, especially when new [88]. Grains, especially at the bottom of the bags, are susceptible to molding due to moisture absorption from the ground when the bags are not placed on pallets, as the case is for most small-scale farmers. In comparison with hermetic storage bags, woven PP was found to have the highest MC after 9 months of storage [120]. This interaction with the environment may result in consequential grain weight and bulk density changes due to continued loss and gain in moisture. Although the grain bulk density was reduced for all storage units considered in the study over the storage period, Melese et al. [120] observed significantly higher losses with the woven PP compared to the hermetic counterparts. The study attributed the losses to high insect infestations.

6.2.2. Improved Storage Techniques

Despite the large-scale grain storage, community storage structures and warehouses do not effectively protect grain from rodents, insects, pests, and mold [34]. Stored grain pests feed and bore the grain kernel, destroying the germ. They also cause heat and deteriorate stored grain products, resulting in huge losses due to nutritional depletion and market value reduction, as well as contamination by their excretory products, which can be extremely hazardous to humans [121]. Grain quality within the community storage structures and warehouses is anchored in structural maintenance. A well-maintained structure with no openings to cause grain wetting during precipitation and well plastered walls and floors to eliminate entry and growth zones for the insects or rodents would be ideal for effective grain storage [107]. Unfortunately, this is not quite common, as structure development and maintenance are quite costly, and poor farmers are not willing to invest their little profits gained from the sale of grains into structural development. Additionally, insect infestation could be attributed to poor sanitation during grain handling at the warehouses. A study by Manu et al. [34] on grain warehousing in Ghana associated the presence of *P. interpunctella* in warehouses with poor sanitation within the facility and the surrounding environment. Farmers are left with no choice but to continue using the chemical pesticides to augment the efficiency of the community structures and warehouses [95]. Manu et al. [34] reveal that the warehouse with frequent application of deltamethrin insecticide had the lowest moth capture at 1.5 individuals per trap.

Although it started way back with the use of biopesticides such as plant leaves, oil, cow dung, turmeric or onion rhizomes, mint leaves, neem leaves, eucalyptus, and ashes for grain storage [18], the use of insect repellants has lately increased, especially due to the inefficiency of different grain storage systems. Biopesticides are derived from natural materials and offer an eco-friendly alternative to synthetic pesticides. However, biopesticides such as cow dung affect the sensory attributes of the stored grain. The use of synthesis pesticides is observed in storage bags, community storage structures, and warehouses [107]. Synthetic pesticides are derived from chemicals and are extremely fast and effective compared to biopesticides. However, the use of chemicals also has negative effects on the environment and could lead to the development of insect resistance [115]. Despite their effectiveness at improving the efficacy of other storage systems, chemical-based repellants have been widely criticized for their negative effects on grain quality. The use of synthetic insecticides may result in the accumulation of chemical residues on the stored grains [91], posing health threats such as anti-microbial resistance. The practice is never regulated, leaving the farmer with no guide on the application rate. Eventually, the grain chemical application supersedes the nominal acceptable levels based on the market requirement, rendering the grains of low quality. Chemical residual limits are in line with the Sanitary and Phytosanitary (SPS) measures set up to promote sustainable production and trade by helping maintain plant, animal, and human health. Maximum residual limits (MRL) and mycotoxin levels are integral to the SPS system as they safeguard human health [122]. MRL varies from market to market and is not enforced in several economies. Nonetheless, it is a great concern for the international market. It is evident that the potential market gains from the continent's continuous high grain production are constrained by the high mycotoxin levels and residual chemical levels. Residual limits are a critical market entry barrier for exporters [122]. Additionally, overuse of insecticides poses a food safety challenge [97]. Some studies have reported that chemical application as a grain preservation method reduces the seed viability [123] and makes the seed hard, thus requiring increased cooking time. Synthetic pesticides have been identified to affect the nutritional and sensory grain properties [124].

Bin storage silos are prone to temperature accumulation within the grain mass in hot weather, especially in systems with no proper aeration. This eventually induces natural convection currents within the grain mass, thus facilitating overall moisture movement within the grain bulk. A study by Jian et al. [125] found that the temperature gradient within the grain mass was large enough to trigger moisture movement within the grain mass. This study further reveals that the change in moisture at the top of the grain mass was so significant compared to the grain bulk, indicating moisture movement. Additionally, there is potential for water ingress and seepage, especially if the system is not well maintained. The presence of warmth and moisture facilitates respiration within the grain mass. The combination of temperature and moisture creates favorable conditions for mold development and insect activity, leading to grain quality losses and the loss of dry matter [39,93,95,114,126]. In summary, the best results of grain quality control can only be achieved with proper management in the form of proper aeration and structure maintenance.

The development of HSTs is by far the most successful innovation in grain storage in the African context. Several researchers have documented the effect of HSTs on grain quality in the form of seed germination, insect infestation, molding, grain breakage, and nutritional losses. HSTs maintain the physio–chemical composition and physical structure of the grain. Aboagye et al. [95] compared hermetic and non-hermetic storage of cowpeas in Ghana. The study revealed that hermetic storage stabilized grain MC and an insect mortality rate of 100% over the storage period. Also, a high proportion of grain maintained its wholesome structure in hermetic storage compared to the non-hermetic units. Mubayiwa et al. [127] found that hermetic technologies exhibited superior grain protection characteristics in terms of grain damage, weight loss, insect pest populations, and grain MC compared to synthetic pesticide-based sorghum storage technologies in Zimbabwe. A study by Dijkink et al. [89] revealed significant insect damage on maize kernel after 100 storage days for standard bag (woven PP) and pesticide-based standard bag (woven PP) storage compared to hermetic bags with minimal losses of 2%. All HSTs take pride in preventing insect infestation, stopping aflatoxin development, and preserving seed quality without the use of insecticides [97], critical challenges that are currently facing the grain industry in Africa.

7. Perspectives for Improved Grain Quality in Africa: Lessons from Successful Post-Harvest Drying and Storage Models in Africa

This study details the close drying-storage interactive effect on grain quality. Thus, management of PHLs at storage without addressing the underlying grain handling issues during drying may only help in the short term. Learning from previous projects and sharing successes is valuable. This section draws lessons from successful and potentially scalable PH drying and storage models applicable to the Africa setting to infer guidance for system-based approaches for promotion of optimal drying and storage options. This study adopted three models (cob model, WFP Zero Food Loss Initiative model, and AflaSight Project model) as case studies for the effective management of grain quality post-harvest initiatives in Africa. Although the models share some commonalities, the cob model focuses on off-farm storage while the other uses on-farm storage. The AflaSight model, however, focuses on corrective action through the removal of aflatoxin from already infected maize kernels at an industrial scale. The three evaluated models contribute to at least one of the following outcomes: increased adoption of improved drying and storage technologies; increased agricultural productivity; increased incomes and welfare for farmers; improved market access and price stabilization; reduced malnutrition; improved food security; increased agricultural value addition; and national economic growth, among others. For instance, the on-farm grain storage observed in the WFP Zero Food Loss Initiative model and off-farm storage under the Cob model facilitate the developing communal and national food security and nutrition agendas, respectively. Farm-gate price stabilization and market access facilitate increased involvement of the population in the '*dirty*' venture. Increased investment in grain value addition is possible under the Cob and AflaSight models. The detailed evaluation of the models is as follows:

7.1. The Cob Model—Rwanda

The cob model is one of the innovative approaches being utilized to improve maize quality by addressing aflatoxin contamination in Rwanda [128]. The model is implemented by public–private partnership (PPP) Africa Improved Foods (AIF) by the Royal DSM, the Dutch entrepreneurial development bank (FMO), the British Department for International Development (DFID), the International Finance Corporation (IFC), British International Investment, and the Government of Rwanda. The model is based on two hypotheses for controlling aflatoxin among grains: (i) minimizing the lag between harvesting and drying, and (ii) delaying the shelling of corn until prior to drying [129]. A study by Mora and Lacey [130] found that delayed shelling prior to drying and minimizing the lag between harvesting and drying could reduce post-harvest aflatoxin contamination. The model guides farmers to suspend their de-husked cob maize on rails in a designated shade before consolidating them in woven PP bags for transportation to the shelling center. Subsequently, the grain kernels are promptly dried at the AIF factory following the shelling process. In this model, the maize is sourced from farmers while on cob at farm-gate price within 2 days from harvest. The corn is then shelled using semi-mobile mechanical systems stationed at communal locations. Shelled maize is then transported to AIF for industrial drying and storage (Figure 9). Drying and storage are done on the same day using state-of-the-art equipment at the AIF factory. For concerted efforts, farmers are collectively trained in best handling practices during harvesting through partner cooperatives. This partnership strengthens mobilization and training activities among farmers. Thus, cooperative systems can easily adopt the approach, enabling scalability in Africa, where agribusinesses were founded on cooperatives. It is estimated that the implementation of the model improved grain quality by about 85% [131]. Local sourcing of raw material for the AIF industry has since increased from 20% in 2017 to about 60% in 2021, with subsequent reduction of maize rejects due to aflatoxins from 90% to less than 10% within the same period [132]. There is evidence of improved farmers' incomes given the reduced losses at farm level. AIF offers a ready market for maize, thus increasing overall productivity for the crop. The model is non-discriminatory, as both men and women are equally enrolled in project activities. Additionally, the hanging of de-husked cob maize and off-farm drying further creates time for women and children to participate in other production roles [131]. The cob model bridges the farmer–agro-processors gap, therefore improving value chain performance. It therefore saves the rural farmers the burden of huge postharvest costs just to maintain the grain for future sale. The model reduces grain handling among farmers, making grain less susceptible to contamination by animals and dust, as observed in open-sun drying. Consequently, economically disadvantaged small-holder farmers can ably enjoy the benefits of improved drying technologies that were previously exclusive to large-scale commercial farms and processing firms.

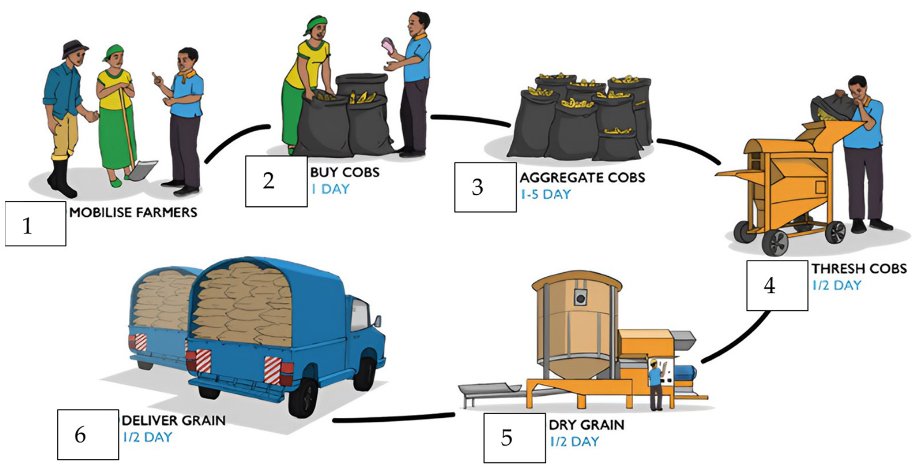


Figure 9. Flow of activities under the cob model [133].

7.2. The WFP Zero Food Loss Initiative Model—Uganda

Initially implemented in Uganda, the WFP-funded project aimed to scale up the fight against PHLs through capacity building and the provision of alternative grain handling equipment. The project's evolution can be traced in several sub-Saharan countries [134]. The theory of change is well explained by Viola [134]. The adoption of post-harvest management training, along with the utilization of hermetic storage equipment, allowed farmers to significantly reduce their post-harvest losses. The project prioritized three types of storage equipment, including metal silos, plastic silos, and super grain bags. This approach provided a wide range of grain hermetic storage (HST) options to cater for individual and group-based farming initiatives. Each storage unit was sold with a tarpaulin commensurable to its capacity to cater for varying financial strength. Although the model co-opted open-sun drying as the drying mechanism, farmers were given prior training on best practices for open-sun drying. It was emphasized that all grains are dried on the tarpaulins distributed with the storage equipment. The project employed a phased subsidy approach to facilitate quick adoption and farmer interaction with technology. They hypothesized that 'word-of-mouth' based on the benefits of the technologies will facilitate successful penetration and use of the technologies among farmers [135]. The model used established structures such as cooperatives and local manufacturing facilitates and PPP to enforce its operations. Several players, including but not limited to research and civil society organizations, were brought onboard to facilitate the quick proliferation of the technologies among the population. Awareness, training in HST use, and improved technology supply chains paid off given the great urge for the use of HST over the conventional storage methods that manifests among grain handlers [90,97,136]. Production and distribution of HST was done by local manufacturers and private sector distributors, as WFP offered oversight roles. Capacity building adopted a wholesome training approach—where farmers were trained in effective grain handling at four value chain nodes, including harvesting, drying, threshing, and storage [87,135]. Training of Trainers (ToT) was done to facilitate proliferation of knowledge on PHL within communities through participatory training. A study by Okori et al. [90] in Uganda revealed that training in hermetic storage significantly affected farmers' decisions to adopt HSTs. There is potential that grain storage quality losses in the form of seed germination, insect infestation, molding, grain breakage, and nutritional losses could reduce since the technology is designed for the small holder farmers that make the greatest potion of the farming workforce. The success stories triggered several campaigns towards the adoption of HST for several other grains within SSA, years after the project. This transition resulted in a decrease in PHLs from 60% with traditional storage methods to less than 2% when employing the innovative technologies within the first months following harvest in Uganda [135].

7.3. The AflaSight Model—Rwanda

The project aims to support efforts towards the reduction of aflatoxin levels in Rwanda without disrupting the already existing value chains. The project was implemented by AflaSight, a local startup in Rwanda, with support from WFP, IFC, and Vanguard Economics. The model approach is two-fold: (i) establishment of 'AflaKiosks'—mobile grain testing stations to provide free testing services to traders and farmers; and (ii) the AflaSight—a grain detection, sorting, and treating technology to facilitate non-destructive treatment of aflatoxin-infected maize [137]. The AflaSight project model pioneered its AflaKiosks operations with two mobile testing facilities supporting 10 strategic grain trading hubs across Rwanda and four cooperatives under the grain-treatment strategy [137,138]. AflaSight uses Bühler's LumoVision technology to remove aflatoxin-infected kernels from batches of maize grain. It also provides drying and cleaning services and engages in market operations with traders (and potentially other value chain actors in the future) [138]. This model enables traders and farmers to assess the quality of their grain prior to its sale, thereby granting farmers the opportunity to access a wider range of markets and secure improved prices for their uncontaminated maize. Although the model is still in its infancy stage with more rigorous testing and evaluation of adoptability required, the results indicate immense potential for aflatoxin reduction. AflaSight can process up to 20 metric tons of maize per hour while reducing aflatoxin levels by up to 90% [138]. This is accomplished with only a 5% volume loss. Therefore, farmers can remove aflatoxin from maize in a safe manner and sell the resulting crops in high-priced markets. This strengthens regional food networks, increases farmers' incomes, and improves the quality of locally available foods. High-quality grain is expected to improve market reliability, reduce import costs, and encourage agricultural value chain investments.

The models reveal strategic pathways for the successful implementation of improved grain-quality interventions during drying and storage. Firstly, treat the value chain as a system. It is evident that in almost all models, key stakeholders, including small-scale farmers, cooperatives, agro-processors, policy makers, and civil society organizations, among others, jointly contributed to the success of the projects. The system approach is currently being promoted as the most reliable methodology to address the dynamic food systems in low- and middle-income states [139]. Food systems encompass a comprehensive range of activities and resources that play a pivotal role in the production, distribution, and consumption of food. The activities and resources are influenced by several factors and have a substantial effect on the overall outcomes of the food system. The systems approach places emphasis on the interrelationships and feedback mechanisms among constituent components of the system [139,140].

Secondly, the use of sustainable approaches is critical for improved grain quality. The models evaluated emphasized sustainability through gender inclusion, sustainable financing options, and the use of existing infrastructure alongside novel interventions. The uptake of postharvest inventions aimed at grain quality improvement is challenged by lack of knowledge, lack of access to markets, credit constraints, limited access to extension services, labor, and other resources necessary for the use of technologies, and the appropriateness of the technologies. These challenges are broadly categorized into three phases: awareness, tryout, and continuous adoption [29,141]. The constraints are, however, aggravated by gender issues. According to Mayanja et al. [142], gender relations and household dynamics related to decision-making may influence the levels of technology adoption. In Africa, gender inequality remains high, and progress towards parity is still slow [143]. The gender division of labor is still eminent in agricultural activities in Africa. For instance, the men find markets and negotiate prices regardless of who harvested or prepared the commodity. Some husbands of women entrepreneurs are reluctant to allow their wives to travel or do business with other men because friends and family may judge. The women may assist the man in finding a market, but they cannot sell or negotiate prices. It is therefore evident that gender issues related to division of labor and access and control of resources greatly influence the nature and extent of postharvest technology adoption. That withstanding, women show significant involvement in alternative agricultural initiatives [144]. Engendering grain quality enhancement programs is therefore critical for successful implementation. Additionally, the agricultural sector in Africa is largely subsistence and characteristic of cooperative arrangements. The evaluated models use the cooperatives as entry points and training structures. Cooperatives facilitate peer-to-peer, experiential, and network learning, critical strategies for effective technology transfer extension programs. This further explains their extent of success. The development of alternative technologies with multiple payment options, as with the WFP Zero Food Loss Initiative model, increases the potential for technology adoption among farmers. The role of subsidies should not be neglected, as it communicates directly to the marginalized poor communities, enabling them to participate in the drive for improved grain quality. Co-financing of grain handling operations is critical. It is evident that whereas the three models created avenues for farmers to benefit from the project, they were responsible for primary activities ranging from growing grains to harvesting. It creates a sense of ownership among the project beneficiaries.

Lastly, there is a need to establish and implement enabling policies through political will to improve grain quality at the national and continental level. The fact that postharvest operations such as drying and storage are not done in isolated systems means policies are critical to harmonize the interaction among several factors. Additionally, strategies such as relieving farmers off the post-harvest operations, as the case is in the Cob model, in exchange for money at the farm gate price require critical monitoring to ensure that the farmers are not frustrated enough to abandon the transition.

8. Conclusions

This study sought to evaluate the close grain quality relationship between drying and storage with an appraisal of operations in Africa. It identified significant flaws in drying and storage infrastructure and practices, which, despite their contribution to food security and economic transformation, are often inadequate. A key finding is the widespread use of inappropriate drying techniques, such as open-sun drying, which leads to uneven drying and increased mycotoxin levels, posing serious health risks.

The study highlighted the potential of improved technologies like solar dryers, which offer better quality control without increasing energy demands. While traditional storage methods were largely ineffective, open-fire storage showed promise in reducing insect infestation, improving viability and germination, and maintaining nutritional value, though its use is limited.

The review emphasized the success of small-scale hermetic storage technologies (HST) in Africa, which significantly improves grain storage by preventing oxidation and inhibiting insect and fungal growth, thus maintaining grain quality. These technologies are particularly suitable for smallholder farmers due to their low cost and effectiveness.

Three models native to Africa—the Cob Model and AflaSight Project in Rwanda, and the WFP Zero Food Loss Initiative in Uganda—were analyzed in this study as examples of successful grain management interventions. These models integrated system thinking, gender inclusion, sustainable financing, and political support to create a comprehensive approach to improving grain quality. The study suggests adopting these models to enhance grain management practices, improve food security, and foster economic growth across Africa.

In the short term, the study recommends that grain handlers implement better management protocols during open-sun drying to mitigate quality deterioration. Consortium-based implementation of the reviewed models could lead to significant improvements in grain quality and market opportunities, thereby contributing to broader economic transformation in the region.

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