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Developments in the use of hermetic bags for grain storage

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1 Introduction

Postharvest management of agricultural products is a significant challenge in developing countries. Postharvest management, including handling and storage, play a vital role in keeping agricultural commodities safe from deterioration. Important staple crops such as maize, wheat, rice, and beans are susceptible to storage losses mostly due to insect pests. There are several grain storage techniques, including traditional/local methods, pesticides, and hermetic systems. The storage systems' most important feature is to preserve the integrity of the grain for a given period with minimal loss in quality and quantity.

Hermetic technologies as an alternative to traditional and chemical control methods have gained significant interest among farmers, the private sector, governments, and development agencies. Hermetic technologies owe their effectiveness to the airtight conditions created during storage. Biological processes such as respiration and metabolic activities are driven mostly by the presence of insects and other biological activities that lead to the depletion of oxygen and release carbon dioxide inside hermetic containers

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(Murdock et al., 2012). Hence, the hypoxic environments these technologies create become unfavorable to the development and reproduction of insect pests and thus minimize or stop grain damage. Commonly used hermetic technologies include silos (metal and plastic), drums, cocoons, plastic bags, and other containers. These hermetic containers come in different forms and sizes.

Among hermetic technologies, hermetic bags are the most widely disseminated among smallholder farmers in sub-Saharan Africa (SSA) and Asia. The use of hermetic bags to store grain has significantly increased in the past 10 years, spearheaded by the development of the Purdue Improved Crop Storage (PICS) bag. The adoption of hermetic bags is driven by several factors, including: (i) the severity of storage losses at the farm level; (ii) the efficacy of the technologies, and (iii) other benefits such as being chemical-free, cost-effective, easy to use; and locally available. Hermetic bags significantly reduce food safety risks posed by the conventional method of treating stored grains with insecticides.

There are several commercially available types of hermetic bags: single-layer (e.g. SuperGrainbags™ bags manufactured by Grainpro Inc.), double-layer (e.g. AgroZ bags manufactured by A to Z), and triple-layer bags (e.g. PICS™ bags manufactured by several licensed plastic companies in SSA, Asia and Latin America) (Villers et al., 2006; Jonfia-Essien et al., 2010; Murdock and Baributsa, 2014; Coffi et al., 2016). These hermetic bags come in different forms and sizes, and most of them look similar to transport or storage containers (polypropylene [PP] woven bags and plastic polyethylene [PE] liners) that are regularly used by farmers. Hermetic bags are appropriate alternatives to traditional and conventional storage methods as they maintain the quality of stored products and allow smallholder farmers to be food secure and have the flexibility to sell their grain when prices are high.

2 Development of hermetic storage bags

Hermetic storage is not a new concept and has been recorded from prehistoric times when grain was stored underground in pits (Navarro et al., 1994). Hermetic bags are an adaptation of the traditional and other forms of hermetic storage systems such as underground pits, clay pots, jerrycans, silos, or drums. Underground pits were considered as a traditional method of storage that provides an airtight, chemical-free, and safe means to store dry crops (Navarro et al., 1994). The development of hermetic bags started in the 1980s with the PICS in Africa and the Cocoon in Israel (Kitch and Ntoukam, 1991; Navarro et al., 1993; Murdock and Baributsa, 2014). GrainPro's SuperGrainbags™ emerged out of this effort to develop solutions for smallholder farmers. Hermetic bags were developed to help smallholder farmers in developing countries reduce postharvest losses due to insects. Unlike some of the other hermetic storage methods such as jerrycans, or drums, hermetic bags can be easily scaled up cost-effectively.

The PICS technology was developed by Purdue University to address storage pest infestations on cowpeas (*Vigna inguiculata*, L. Walp.) in West and Central Africa (Baributsa et al., 2010, 2014a). Cowpea farmers in West Africa lose a substantial portion of their harvest (from 10% to as high as 100% after only a few months) during storage due to insect pests (*Callosobruchus maculatus*, Fabricius) (Moussa et al., 2011, 2014). PICS bags were developed to provide farmers with a chemical-free and cost-effective storage method. Existing storage methods such as granaries, ash, sand, botanicals, metal drums, jerrycans, and insecticides had shortcomings. Some of these methods were ineffective, costly, not scalable, and posed health risks. Providing a safe and cost-effective method to store grain would improve food security and also allow farmers to tap into better grain prices during the lean season. PICS bags come in three different sizes – 25 kg, 50 kg, and 100 kg bags. Each bag is made of two high-density polyethylene (HDPE) liners that are fitted inside a PP woven bag. PICS bags are manufactured by 15 plastic companies around the world. Eighty percent of PICS manufacturers are located in SSA, while the rest are in Asia and Latin America; as the latter are newly emerging markets for the PICS technology.

The development of hermetic bags by GrainPro started with the deployment of large-scale plastic storage structures (cocoons) for long-term grain storage. These cocoons come in different sizes of up to 300 tons. Over time, GrainPro developed intermediate and small storage systems, which are based on the hermetic principle. The small-scale hermetic storage system of GrainPro is the SuperGrainbags™, which are storage containers suitable for subsistence farmers (Jonfia-Essien et al., 2010). GrainPro hermetic systems became commercially available in the early 1990s, and today they are in use in more than 32 countries around the word (Villers et al., 2008). The SuperGrainbags™ were initially used for storing rice seeds as part of the 5-year project of the International Rice Research Institute (IRRI) in the Philippines (Villers et al., 2006). Each SuperGrainbags™ is a thin single multi-layered plastic liner, which is transparent and has low oxygen permeability. The capacities of SuperGrainbags™ can range from 60 kg to 1000 kg; 60–90 kg capacity being the most common (Villers et al., 2006, 2008). GrainPro bags are manufactured in Subic Bay in the Philippines and shipped around the world.

In the last 5 years, several other brands of hermetic bags (Table 1; Fig. 1) have emerged, innovating on or imitating existing ones. These include ZeroFly® hermetic storage bag, AgroZ bag, and Elite bag. AgroZ and Elite are

Table 1 Characteristics of hermetic bags being sold in sub-Saharan Africa in 2019

Type of hermetic bags	Woven bag (PP)	Liners	Examples
Triple bags	One PP bag	2 HDPE inner liners	Purdue Improved Crop Storage (PICS)
	One PP bag	2 HDPE inner liners	Elite Bag Light Duty Double Liner
Double bags	One PP bag	1 liner with multiple layers	AgroZ
	One PP bag	1 liner with multiple layers impregnated with insecticides	AgroZ Plus
	One PP bag impregnated with insecticides	1 liner with multiple layers	ZeroFly Hermetic storage bag[a]
Single bag	No	1 liner with multiple layers	GrainPro Bag Zipper

[a]Polypropylene/woven bag is impregnated with Deltamethrin to prevent the infestation from outside the bag.

Figure 1 Hermetic storage bags commercially available in Kenya in 2019.

manufactured in East Africa, while ZeroFly bags are imported from outside Africa. The development of these hermetic bags was mostly driven by the realization of the growing demand for safer and affordable storage technologies among smallholder farmers. AgroZ bags are double-layer bags (one-liner and one woven bag) developed by A to Z Textile Mills Ltd (Tanzania). The liner is co-extruded combining HDPE, Metallocene Linear Low-Density Polyethylene (MLLDPE), and low-permeability barrier layers limiting the passage of oxygen. Another hermetic bag developed by A to Z Textile Mills Ltd is the AgroZ bag Plus, which is a premium product, insecticide-treated hermetic storage bag, specifically designed to control larger grain borer (*Prostephanus truncates*, Horn). The ZeroFly hermetic storage bag is manufactured by Vestergaard and is composed of an outer PP bag impregnated with deltamethrin and an inner multilayered recyclable PE bag with a gas barrier. Elite Innovations (K) Ltd, based in Kenya, also developed a double-liner hermetic bag made from HDPE called Elite Bag Light Duty Double Liner.

3 Hermetic bags for grain storage

3.1 How does it work?

Most hermetic bags consist of two basic components: (i) an inner liner (single or double), and (ii) an outer bag. The inner liner could be an individual or multilayered film designed to provide a gas barrier, which is the most critical component of the hermetic bags. The outer bag is a PP bag designed to provide strength and protection during handling. The hermetic bags work under the principle that the bio-generated modified atmosphere created by the metabolic activities of organisms is present in the commodities. Insects and microorganisms consume oxygen and release carbon dioxide, hence generating a low-oxygen environment (Fig. 2). The created hypoxic conditions inhibit the growth and development of insects and mold, thus, preventing grain deterioration. The plastic inner liners of the hermetic bag are designed to limit or sensibly reduce the permeability of gases to ensure that the low-oxygen environment inside the bag is maintained to levels that hinder the development of all life stages of insects. When the inner liner is pierced, the technology loses its efficacy, and the bag should be replaced in the case of single, double or triple hermetic bags. For brands of hermetic bags that are triple bags, the second liner provides extra safety in case one of the two liners is damaged. Insects rarely damage the second liner of the triple-layer bags;

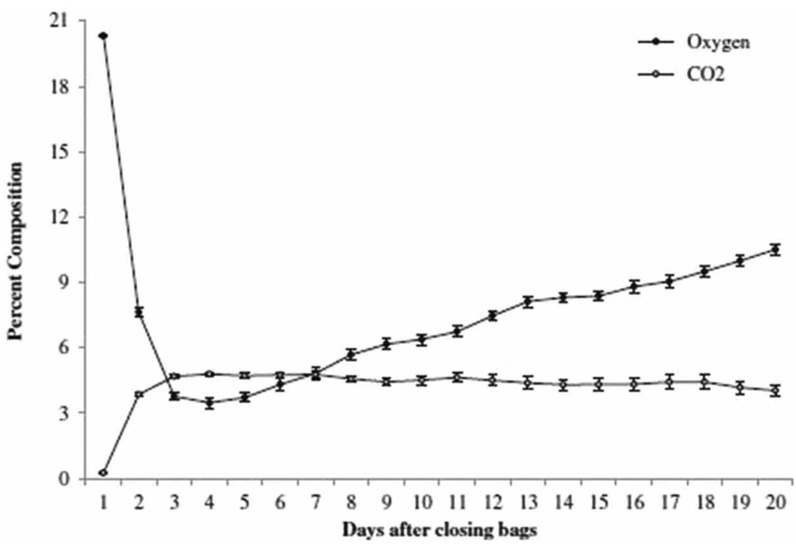

Figure 2 Changes in the concentration of oxygen and carbon dioxide inside a PICS bag filled with mildly infested cowpea grain. Gas levels were monitored for 20 days using a Mocon Headspace analyzer (Murdock and Baoua, 2014).

hence, the technology can still provide protection during grain storage. Minor damages such as holes can be repaired with adhesive tape. Otherwise, the bag needs to be repurposed for other uses or recycled (Baributsa et al., 2014b).

All hermetic bags currently on the market rely on natural processes to achieve hypoxia. Research efforts to develop technologies that could deplete oxygen inside hermetic bags once the containers are closed have not been developed. This concept of adding oxygen scavengers to hermetic bags will become crucial as the use of these technologies expands to new crops or commodities that require a sharp reduction in oxygen levels not only to kill insects but also maintain food quality such as vitamins. A study conducted at Purdue University showed that adding oxygen scavengers into grain stored in PICS bags helped reduce the degradation of pro-vitamin A in biofortified orange maize (Nkhata et al., 2019). Also, the use of a controlled atmosphere to achieve a low-oxygen environment needs to be explored, especially for its application in developed countries where tolerance for insect presence in grains in minimal/low.

3.2 Efficacy of hermetic bags for grain storage

The efficacy of hermetic bags to protect grains and other stored products has been documented through research. Though there is a difference in the composition of hermetic bags (single, double or triple bags) and how liners are designed (single- or multilayered liners), little or no significant differences have been observed in the efficacy of these technologies. Published research on five hermetic bags currently being commercialized in Kenya and other countries in SSA is presented in Table 2. Studies have shown that hermetic bags are as effective as and sometimes better than insecticides in reducing storage losses due to insects (Baoua et al., 2012a; Baributsa and Njoroge, 2020; De Groote et al., 2013; Mutambuki et al., 2019).

Hermetic bags preserve grain and seed quality, but maize must be properly dried before storage in airtight conditions (Williams et al., 2014; Walker et al., 2018). Hermetic bags can achieve 100% insect mortality and reduce losses to less than 1% after several months of cereal (maize, *Zea mays* L., and paddy rice, *Oryza sativa* L.) storage (Baoua et al., 2014a; De Groote et al., 2013; Guenha et al., 2014; Njoroge et al., 2014) and legume crops such as common beans (*Phaseolus vulgaris*), mung beans (*Vigna radiata* (L.) Wilczek), pigeon peas (*Cajanus cajanus* (L.) Millsp), and Bambara nuts (*Vigna subterranea* (L.) Verdc.) (Mutungi et al., 2014, 2015; Baoua et al. 2012b, 2014b; Vales et al., 2014). For seed storage, research findings have shown that hermetic bags have a tolerable reduction in germination (Afzal et al., 2017; Guenha et al., 2014). Beyond insects, hermetic bags have shown to be effective at mitigating grain contaminants such as mycotoxins. Laboratory and field experiments have demonstrated that

Table 2 Summary of research on hermetic bags being sold in sub-Saharan Africa in 2019

	Focus of study	Type of hermetic bag	Type of crop	Source (location of study)
1	Grain damage due to insect infestation, insect mortality and seed viability	PICS bag	Cowpea	Sanon et al. (2011) (B. Faso); Baoua et al. (2012a,b) (Niger); Murdock et al. (2012) (Niger); Baoua et al. (2013) (Niger); Ibro et al. (2014) (Nigeria, Niger and B. Faso)
			Dry common beans	Mutungi et al. (2015) (Kenya)
			Maize	Baoua et al. (2014a) (Benin, Burkina Faso and Ghana); Njoroge et al. (2014) (Kenya); Ng'ang'a et al. (2016a) (Kenya); Afzal et al. (2017) (Pakistan); Williams et al. (2017) (USA); Mutambuki et al., (2019) (Kenya)
			Mungbean	Mutungi et al. (2014) (Kenya)
			Pigeon peas	Vales et al. (2014) (India)
			Rice (paddy)	Baoua et al. (2016) (B.Faso, Ghana and Niger)
			Wheat	Martin et al. (2015) (USA)
		SuperGrainBag™	Maize	De Groote et al. (2013) (Kenya); Chigoverah and Mvumi (2016) (Zimbabwe); Ndegwa et al. (2016) (Kenya); Likhayo et al. (2018) (Kenya)
			Rice (paddy)	Guenha et al. (2014) (Mozambique)
		Zerofly bag	Maize	(Ghana)/Paudyal et al. (2017) (Ghana); Abass et al. (2018) (Tanzania)
2	Performance comparison of different hermetic bags	PICS and SuperGrainBag™	Cowpea	Baoua et al. (2013) (Niger)
			Chickpea	Alemayehu et al. (2020) (Ethiopia)
			Maize	Chigoverah and Mvumi (2018) (Zimbabwe); Walker et al. (2018) (Kenya)
			Rice (paddy)	Awal et al. (2017) (Bangladesh)
		PICS, SuperGrainBag™, Agrozbag and Agrozbag Plus	Maize	Coffi et al. (2016) (Tanzania)
3	Fungal contamination/ mycotoxin/aflatoxin	PICS bag	Maize	Williams et al. (2014) (USA); Ng'ang'a et al. (2016b) (Kenya); Tubbs et al. (2016) (USA); Maina et al. (2016) (Kenya); Lane et al., (2018) (USA)
		SuperGrainBag™	Maize	Kumari et al. (2017) (India)
4	Economic benefits	PICS bag	Common beans	Jones et al. (2011b) (Tanzania)
			Cowpea	Moussa et al. (2011, 2014) (West and Central Africa)
			Maize	Jones et al. (2011a,) (Malawi, Mozambique, Ghana and Tanzania)

hermetic bags can be used to arrest mold growth and aflatoxin development (Williams et al., 2014; Tubbs et al., 2016; Lane et al., 2018). New applications include the use of hermetic bags to store and transport coffee and cacao to prevent insect attacks, mold, and the loss of aroma and flavor (Jonfia-essien et al., 2010; Donovan et al., 2019).

4 Dissemination of hermetic bags to reduce postharvest losses among smallholder farmers

In recent years, postharvest storage losses among smallholder farmers in SSA Africa have gained the attention of government, donors, and the development community. Several organizations and projects have made efforts to scale up the adoption of hermetic storage in SSA. With a grant from the Bill and Melinda Gates Foundation (BMGF), Purdue University (Indiana, USA) initiated large-scale dissemination of hermetic bags in SSA starting in 2007 (Baributsa et al., 2010). Then, the PICS technology was being disseminated in ten countries in West and Central Africa to reduce on-farm storage losses of cowpea. In 2011, the PICS bags were tested for the storage of grains beyond cowpea, including maize, common beans, and cassava chips (Baoua et al., 2014b; Hell, 2014; Njoroge et al., 2014). PICS bags proved to be effective in storing several dried products. The bags were still branded as PICS, but the ‘C’ was changed from ‘Cowpea’ to ‘Crops’. PICS bags have been commercialized in SSA, Asia, Latin America, and the Caribbean (Baributsa, 2019). More details of this effort are discussed in the case study on PICS.

Several years after the initial launch of the PICS program, many public, private, and development agencies saw an opportunity to promote hermetic storage bags in SSA. GrainPro Inc., a private company that was promoting SuperGrainbags™ for rice storage in Southeast Asia, saw an opportunity to expand its market to Africa. In fact, in 2010, there was a discussion between Purdue University and GrainPro Inc. for a potential partnership to scale up the adoption of hermetic bags in SSA that resulted in a Memorandum of Understanding for collaboration in research between both organizations. As the interest of the private sector continued to grow, plastic companies innovating on or imitating existing hermetic bags came into the market. Countries like Kenya saw a substantial increase in the number of hermetic bags on the market due to a potential demand among farmers (Baributsa and Njoroge, 2020). The growth in the commercialization of hermetic bags to smallholder farmers was also propelled in part by investments from government and donors in disseminating hermetic technologies.

In 2013, PICS bags were introduced to farmers in Kenya through 850 demonstrations in villages, markets, and farmers groups (Baributsa and Njoroge, 2020). Further dissemination of PICS bags from 2013 to 2016 were

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implemented by several projects including the Kenya Agricultural Value Chains Enterprises Project (KAVES) (Foy and Wafula, 2016). Building on its initial successes, KAVES in collaboration with the Government of Kenya organized roadshows and media advertisements to increase awareness and competition among several hermetic bags, including PICS, AgroZ, SuperGrainbags™, Zerofly, and Elite. In addition, in 2014, AgResults was launched by a consortium of development partners to commercialize hermetic technologies (plastic bags, plastic tanks, and metal silos) to smallholder farmers in Kenya through private-sector competition (AgResults, 2019). Nine companies were selected to be part of the competition – African Farms and Markets Ltd/GrainPro, A to Z Textile Mills Ltd, Bell Industries Ltd/PICS, Corporate Business Forms Ltd/Vestergaard, Elite Innovations (K) Ltd, Ekima Engineering Workers, Kenya Promotions and Marketing Company Ltd, Kentainers Ltd, and Post Harvest Africa. The AgResults intervention included several hermetic bags : PICS, AgroZ, SuperGrainbags™, Zerofly, and Elite bags (AgResults, 2018a). Bags type varied by the manufacturer (Table 1) and the capacity ranged from 50 kg, 90 kg, 100 kg, and 250 kg. Between 2015 and 2018, about 1.4 million storage devices were sold, and the activities reached 220 000 smallholder farmers (AgResults, 2018b). At the end of the project, AgResults awarded over US$6.25 million to three companies that reached the threshold, including A to Z Textile Mills Limited, Bell Industries, and Elite Innovations (AgResults, 2019). It was estimated that AgResults likely increased the adoption of hermetic storage by 23 and 6 percentage point in Eastern Kenya and Rift Valley, respectively. The prize competition initiative to create a private sector-led market for postharvest storage technologies proved to be beneficial to smallholder farmers in Kenya.

Several other postharvest efforts were implemented in other countries, including the *Yieldwise Initiative*. This effort was funded by the Rockefeller Foundation to reduce postharvest losses in Nigeria (tomato), Kenya (mango), and Tanzania (maize). The Alliance for Green Revolution in Africa (AGRA) received funding to implement activities to reduce postharvest losses of maize in Tanzania (AGRA, 2015). Postharvest loss of maize in Tanzania is estimated at 20 to 30% but can reach as high as 40% (Rugumamu, 2004). *Yieldwise* planned to reduce postharvest losses along the maize value chain by clustering 100 000 farmers in groups and training them, linking them to input and output markets, and facilitating their access to finance. The program expected at least 60% of the 100 000 farmers to use loss reduction technologies. These technologies included hermetic storage devices such as cocoons, metal silos, and PICS bags. AGRA as the lead implementer worked with several partners including the government of Tanzania; the World Food Program (WFP); and several local nongovernmental organizations, input suppliers and dealers, commercial banks (e.g. Equity), farmers and farmers' organizations, maize traders and processors, and manufacturers of postharvest technologies (AGRA, 2017). Training of farmers was conducted by WFP in collaboration with local NGOs such as Rural Development Initiative (RUDI) in the Southern Highlands. Financial institutions such as Equity Bank were brought in to provide loans to farmers for increasing access to technologies and to the private sector for supplying inputs and storage technologies to farmers. Several meetings were held between financial institutions, NGOs, partners, and suppliers of inputs and PH technologies to build awareness about the financial products available at the Equity Bank. Data were not available for the impact of this program.

In summary, all these programs proved that there are opportunities to address postharvest losses among smallholder farmers in developing countries. Some of the perceived benefits of using hermetic storage include improved food security and income; and the reduction of insecticide usage. With the increase in the awareness, marketing, and distribution of hermetic bags by the private sector, there is an uptake leading to the reduction of grain storage losses and improved food security. Figure 3 shows that a typical family using four hermetic bags will have an 8.78 extra number of meals equivalent to US$7.20 food saved (ACDI/VOCA, 2017).

Hermetic storage devices could also provide smallholder farmers with the flexibility to store grain for several months while waiting for prices to increase (Swathi and Rajanikanth, 2017). In West Africa, farmers storing cowpea in 100 kg PICS bags made additional cash of US$27 (Moussa et al., 2014). In Kenya, the net gain for storing in hermetic bags ranges from US$18 for maize to US$24 for cowpea (Baributsa and Njoroge, 2020). A recent study conducted in Kenya showed that the major driver for adoption of hermetic bags appears to be health benefits (elimination of chemical use) and labor saving (AgResults, 2019). Additional evidence demonstrates that another health benefit of using hermetic storage technology is the mitigation of aflatoxin growth (ACDI/VOCA, 2017; Tubbs et al., 2016). Several studies have shown that the value of

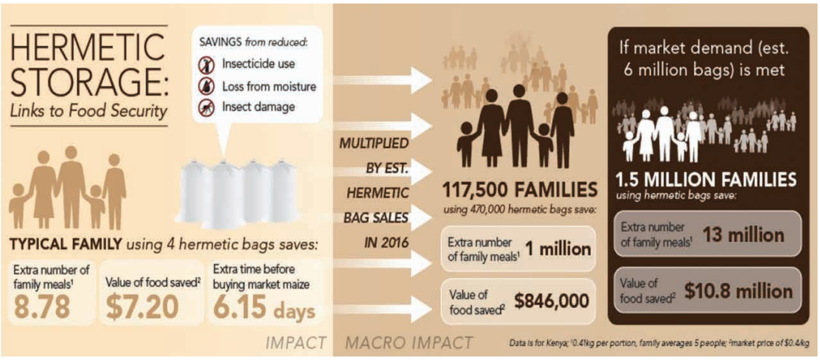

Figure 3 Impacts of hermetic storage bag technology on food security (Source: ACDI/VOCA, 2017).

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reduced storage loss or use of insecticides would easily justify the investment in purchasing hermetic bags (Ameri et al., 2018; Jones et al., 2011a, b; Moussa et al., 2011).

Several factors influence agricultural technology adoption among farmers, including technological, economic, institutional, and human aspects. With the large dissemination of hermetic bags, there are prospects to help smallholder farmers in developing countries improve their livelihood, including increased income, food security, and their health through chemical-free storage of grain and seed. Various authors have identified the following as determinants for the adoption of hermetic storage by smallholder farmers:

- Low cost and affordable
- Simple and easy to use
- Available for farmers
- Can be used to store small or large quantities of grain, seed, and other stored products
- Culturally acceptable
- Locally or regionally manufactured
- Durable or can be used for two or more storage seasons, if handled properly
- Do not affect the seed germination
- Do not affect the biochemical composition of stored products
- Mitigate the development of mold and mycotoxins

5 Challenges in the use of hermetic storage bag technology

Hermetic bags are simple and effective technologies adapted for smallholder farmers who are producing enough grain for home consumption and for sale but have challenges storing it. Though the demand for hermetic storage bags continues to grow with awareness building and training, there is a need to address some of the existing and emerging challenges to further increase adoption among smallholder farmers and other users. Treating smallholder farmers as customers is crucial for improving their experiences in using hermetic bags and for the development of a sustainable supply chain driven by private sector companies.

5.1 Availability

Awareness building and supply chain activities led by extension partners and the private sector have helped to increase the demand and availability of hermetic bags. Despite efforts to disseminate hermetic bags, developing a sustainable bag-distribution network that reaches farmers remains a challenge (Baributsa

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et al., 2010; Govereh et al., 2019; Nouhoheflin et al., 2017). In most countries, farmers often complain about the unavailability of hermetic bags in rural areas (Moussa et al., 2010). The unavailability of hermetic bags can be defined as bags not being available at all for farmers to purchase or being available late in the season after they have already used/purchased other storage technologies. There are areas that have benefited from demonstration activities but do not have vendors who are selling hermetic bags. Others have vendors that are less invested in the business; leading to shortages and late delivery of the hermetic bags to farmers. Challenges in getting hermetic bags at the last mile are linked to the hesitation of retailers and wholesalers to sell a new product, difficulties with enforcing contracts (when reliable vendors are not available), limitations on logistics (i.e. transportation), and, lastly, limited access to capital (Baributsa et al., 2010; Coulibaly et al., 2012). Improving awareness among the supply chain actors including manufacturers, distributors, and retailers could spur their interest in the hermetic bag business. Facilitating linkages to create trust and relations among the supply chain actors is vital to maintaining the flow of the bags to improve availability. The need to expand the production capacity of manufacturers or increase the volume of orders by distributors and vendors may require access to capital from financial institutions. To improve the availability of hermetic bags at the farm level (last mile), there is a need to look into non-traditional distribution systems such as the youth retailer model to sell PICS bags in rural markets or tap into cellphone technology to connect farmers with vendors; both models are currently being tested in Ethiopia (Sertse, 2016).

5.2 Affordability and access

The price of a hermetic bag ranges from US$2 to US$4, depending on the brand, capacity, region, country, and location within a country. While the cost of hermetic bags has not been a major complaint (Moussa et al., 2010), most smallholder farmers have tight budgets. Though most smallholder farmers often lack capital, those who have enough grain to store should be able to acquire hermetic bags by selling small quantities of grain and storing the remainder safely. Those with very little disposable income are more likely to invest in a product after they have had first-hand experience with its viability. Increasing awareness of hermetic bags has shown to increase the willingness to pay among farmers who are non-users (Channa et al., 2019). Thus, creating awareness through training and media activities to ensure everyone (farmers, grain merchants, vendors, and all potential customers in the grain value chain) knows about the benefits of the technology against its cost is still in need. In addition, there are smallholder farmers who often sell a large proportion of their grain at harvest, when prices are low, despite the desire to store. This is often the case for farmers who need cash to satisfy family’s needs. For those farmers who sell immediately after harvest, and buy grain later in the season, there is a need to develop financial products to help them reap the benefits of using hermetic bags. Making loans available at harvest would provide farmers the flexibility to store and sell their crops at higher prices later. Using financing facilities such as the warehouse receipts, farmers can access the much-needed cash at harvest from lenders (e.g. microfinance institutions) and use their harvest (grain) as collateral for loans. Because lenders will have more confidence that the quality of grain can be maintained during storage, they would be willing to give loans to smallholder farmers. Access to such lines of credit can give farmers access to hermetic bags and would increase adoption. To further improve affordability, some private sector companies (e.g. in Ethiopia) have requested government exemption of Value Added Tax (VAT) on hermetic bags. Removing VAT (estimated at 18%) may result in discounts that could be transferred to smallholder farmers and increase adoption.

5.3 Usability and durability

Hermetic storage bags are easy to use and come in different sizes to facilitate handling. Most bags currently being sold on the market have 90–100 kg capacity, though smaller sizes are also available. Farmers prefer larger sizes because the cost of storage is cheaper, and they treat these hermetic bags as granaries (not for transport). Hermetic bags are perfectly scale neutral and can be used to store a few kilograms or a few tons of grain with a lower cost per kilogram than many other storage options currently available to smallholder farmers in many developing countries. Hermetic bags can be tied off just above the grain or filled to capacity as necessary. Other rigid-sided hermetic storage containers such as metal or plastic drums or plastic jugs can be used, but they must be filled completely to be effective; otherwise, they would still have oxygen in them, making the technology ineffective. Trainings through demonstrations or media (posters, radio, videos) have been used to teach farmers how to use hermetic bags properly. Unlike rigid hermetic containers, hermetic bags are susceptible to physical damage due to puncture during handling, abrasions, and perforations from insects and rodents (Manandhar et al., 2018). Proper handling must be employed during transportation and storage to prevent bursting and any physical damage that will compromise their hermeticity, thus, reducing their effectiveness. Trainings equip farmers with the knowledge needed to minimize damages due to handling and rodent attacks (Baributsa et al., 2014b; Baoua et al., 2018; Baributsa and Njoroge, 2020). Simple management practices such as storing clean grain without debris and storing bags on pallets in clean areas and away from direct sunlight will extend the shelf life and usage of the bags. If bags are damaged, farmers can patch small holes or tears with tape to maintain airtightness. The durability of hermetic bags may vary by manufacturer as some brands have single or double liners inside the woven bags. If hermetic bags with a single liner are damaged, their reusability will be limited. Research has shown that PICS bags can store grains for multiple seasons – at least for 3 years (Baributsa et al., 2014b; Baributsa and Njoroge, 2020; Moussa et al., 2014). Just like any other plastic material, mechanical properties of a bag liner are affected by the material composition and thickness. These properties can, in turn, affect the performance and reusability of hermetic bags. This might be one of the reasons hermetic bags have exhibited varying susceptibility to insects such as the large grain borer (Coffi et al., 2016; De Groote et al., 2013; Baoua et al., 2013).

5.4 Need for drying technology and moisture assessment

To maintain quality during storage in hermetic bags, grains must be dried to the recommended moisture content (e.g. 13–14% moisture content for maize). Moist grain/seed stored in hermetic storage bags will result in quality deterioration (e.g. germination loss), or grain will turn into silage (Williams et al., 2014; Tubbs et al., 2016). Mold growth rapidly increases if grains are not properly dried and stored, producing aflatoxin, which causes liver cancer and other health problems (Bankole et al., 2006; Likhayo et al., 2018). Drying and moisture assessment technologies available on the market are either expensive or not adapted to the conditions of smallholder farmers. Finding affordable and cost-effective drying methods and moisture assessment tools should be explored to improve the quality of grain stored in hermetic bags. Low-cost moisture assessment and drying devices have been developed (Ajao et al., 2018; Thompson et al., 2017; Tubbs et al., 2017; Walker and Davies, 2017) but need further refining or dissemination to be adopted by smallholder farmers.

5.5 Need for standards and environmental impact

The scale-up of hermetic bags has proved that smallholder farmers are potential markets for postharvest technologies. Consequently, different brands and qualities of hermetic bags are becoming available to farmers in developing countries; thanks to investments by the private sector. More products in the market will provide farmers with more alternatives and lead to competition. However, competition may eventually lead to the 'race to the bottom', where profit instead of quality products is the major driver of private companies (Baributsa and Njoroge, 2020). Developing a common international approach for testing and rating hermeticity is needed to protect farmers from buying low-quality bags. These proposed standards could use key properties of the plastic inner liner such as oxygen and water vapor transmission rates, and mechanical properties (impact failure, tear, and tensile strength). Overall, there is a need for advocacy to develop hermetic storage technology standards to address low-quality products that could compromise the hermetic bag markets. For instance, the Kenya Bureau of Standards and the East African Grain Council are working with several stakeholders in Kenya to develop hermetic storage bag standards (KEBS, 2019). In addition, government bans on plastic may prevent smallholder farmers from reaping the benefits of using hermetic storage bags. If ordinances banning or regulating the use of plastics are passed, they could reduce access to hermetic storage bags by smallholder farmers. There is a need to engage policy-makers to develop plans for reducing the potential impacts of hermetic bags on the environment. Several hermetic bag manufacturers are involved in recycling and could buy-back and recycle unusable hermetic bags. This would reduce the environmental impact of using plastic to produce hermetic bags.

6 Case study: Purdue Improved Crop Storage (PICS) bag

The PICS technology is a simple, low-cost (US$2.00–$3.00 100 kg bag) storage method for preserving grain without using insecticides. PICS technology is a storage solution for smallholder farmers made of a three-layer bag that includes two liners and an outer woven layer. By creating a hermetic (airtight) seal inside the bag, PICS bags eliminate insect pests, stop mold growth, and maintain grain and seed quality. PICS bags were first developed and disseminated in West and Central Africa for cowpea (black-eyed pea) storage (Baributsa et al., 2010). Later, the bags were tested and disseminated for the storage of other crops including maize, rice, common beans, peanuts, wheat, sorghum, pigeon peas, mung beans, and other dry grains (Murdock and Baributsa, 2014). The use of PICS bags to store grains provides an opportunity to: (i) improve food security by allowing farmers to store grain or other foodstuffs through the lean season when supply is low, (ii) increase incomes of millions of smallholder farmers by providing the flexibility to store grain until prices are higher, and (iii) improve health by mitigating the impact of aflatoxin while reducing insecticide use. The PICS bags also help farmers to preserve their seed for planting, thus increasing availability and improving affordability.

The PICS technology was developed as a response to cowpea farmers' demand for chemical-free and cost-effective storage technology. During the early development of the PICS technology, farmers raised two major concerns: (i) they lacked knowledge on how to use the bags properly, and (ii) the bags were not available locally. To address these challenges, Purdue University and partners designed a program that had two major thrusts: (i) build awareness and train farmers on the proper use of PICS bags, and (ii) develop the supply chain to make PICS available to farmers in rural areas. In each country, the PICS program implemented several activities to build the demand and make the technology available to farmers (Baributsa et al., 2014a).

Market building activities included a cascade of activities that were implemented in a relatively short time – between 4 and 6 months. These activities included:

- ***Identification of partners***: Both service providers and private-sector actors were identified to lead the demand creation and supply chain development, respectively. These partners were chosen based on their experience and capacity to implement their respective activities in a country or region. Service providers included local and international NGOs, national and international research/extension organizations, and farmers' groups. Service providers led the selection of regions, districts, and communities where awareness and training activities would be implemented. The selection of these areas was based on crop production and the severity of storage losses on smallholder farms. After communities were identified, field agents were selected to implement training. The private-sector actors were involved in producing and building the distribution network to make the PICS bags available to farmers in rural areas.
- ***Training of trainers***: These trainings were implemented for the frontline field agents (government extension agents or field agents) who were already working with farmers in local communities. These 1- to 2-day trainings equipped these field agents with the basic knowledge on grain storage challenges (insect pests, mold, rodents, etc.), the economics of storage, strategies to train farmers, monitoring of field activities, and data collection and reporting.
- ***Implementation of village activities***: Several activities were implemented in communities, markets, and farmers' groups to build awareness and train farmers on the proper use of the PICS bags. These trainings were implemented in several steps: (i) awareness building – engage farmers in recognizing the importance of storage losses and introduce PICS bags, (ii) demonstrations – farmers are trained on how to use PICS bags and five pilot farmers in each community volunteer to store grain for several months to test the efficacy of the bags, (iii) follow up – the stored grain is inspected during the storage duration, and (iv) open-the-bag ceremony – the grain stored by the five pilot farmers is opened during a public event attended by the whole community.
- ***Media activities***: Media activities have included radio, television messages, posters and flyers, cellphone videos, short message services (sms), and Unstructured Supplementary Service Data (USSD) code. These activities have played an important role in reaching out to farmers with PICS information. Media helped to: (i) make farmers aware of PICS bags, (ii) train them on how to use the bags properly, and (iii) advertise retail points and provide PICS bag vendors' information to farmers and other users.

- ***Supply chain development***: This involved identifying potential local or regional manufacturers of PICS bags and distributors, and licensed them to ensure product quality and availability. In addition, the PICS program worked with the private sector to market PICS bags to farmers and other users. It is important to note that the huge demands for PICS bags has incentivized the private sector to invest in the manufacturing and distribution of the technology.

Purdue University and partner organizations have led efforts to commercialize the PICS technology, focusing on low-resource farmers in different regions of the world (Baributsa, 2019). Women play an important role in grain storage (Ibro et al., 2014). To increase their participation in PICS activities, all implementing partners were required to have a target of 30% women's participation among field technicians and village activities (Baributsa et al., 2010). The approach used to commercialize PICS is described in Box 1. For the last 12 years, PICS bags have been commercialized in more than 35 countries in SSA, Asia, and recently in Central America and the Caribbean (Fig. 4). The large-scale dissemination of the PICS bags was supported with more than US$25 million in grants funded by the BMGF, USAID, USDA, and several other donors. The BMGF was the single-largest donor with US$23 million, spanning over 12 years in three project phases (PICS1, PICS2, and PICS3). These funds were used to support training

Figure 4 Countries where the Purdue Improved Crop Storage (PICS) bags are being used/disseminated (2019) available (Source: www.picsnetwork.org).

and media activities led by service providers, and to develop the supply chain led by the private sector.

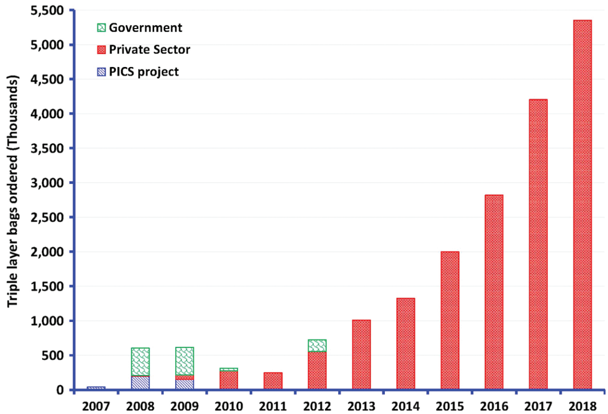
Box 1: PICS's approach to commercialization

- Create the demand by building the capacity of local service providers to raise awareness and train farmers how to use PICS bags
- Target 30% women's (trainers and trainees) participation
- Work with the private sector to manufacture and sell PICS bags to farmers and other users
- Leverage existing efforts by facilitating linkages between the private sector and service providers to increase the demand and availability of PICS bags
- Let the private sector drive the commercialization and service providers continue to provide training on demand.

The PICS1 project (US$12 million) was implemented in ten countries in West and Central Africa (2007–2012) and focused on cowpea storage, cowpea being the most important legume and cash crop for many smallholder farmers in the region (Baributsa et al., 2010, 2014a). Pilot programs were implemented in both Niger and Burkina Faso, with demonstrations in a limited number of villages. This allowed the project to learn and make adjustments for scale-up activities in subsequent years. After the initial pilot effort, the activities were scaled up in the whole region, directly reaching more than 1.6 million farmers in 31 000 villages in West and Central Africa. The PICS2 project (US$1.1 million) was implemented in several countries in SSA and Asia to assess the efficacy of the PICS bags in storing grains other than cowpea including maize, rice, sorghum, common beans, wheat, Bambara nuts, and pigeon peas (Murdock and Baributsa, 2014). The PICS3 project (US$10.1 million), the third phase of the BMGF grant to Purdue, aimed to improve market access and food security as well as expand the commercialization of PICS technology for several crops throughout SSA. The project focused on Nigeria, Ghana, and Burkina Faso in West Africa, and Ethiopia, Tanzania, Uganda, and Malawi in East and Southern Africa. The PICS3 project has directly reached over 2 million farmers in 34 000 villages/communities in SSA. There were efforts to leverage this BMGF grant to increase the use of PICS bags and other hermetic technologies in other countries in Africa and beyond. Additional funding was provided to Purdue University by several donors, including USAID in Kenya, Rwanda, Tanzania, Malawi (more than US$1.2 million) to promote PICS bags and also conduct studies on the impact of credit on storage.

The PICS technology is scalable. Extension activities have scaled the adoption of PICS bags from a few to thousands of villages in several countries in SSA and Asia. Just as PICS bags are a perfectly scalable storage solution for smallholder farmers, they are also very scalable for manufacturing, distribution, and retailing. Several local manufacturers are producing PICS bags around the world, including 12 companies in SSA, two companies in Asia, and one company in Central America. PICS bags are also scalable to the quantity of grain varying from a few kilos to thousands of tons stored by government food security agencies (e.g. the government of Niger purchased 800 000 PICS bags in 2008 to store cowpea). As a result of PICS program activities, millions of farmers have been reached, and millions of bags have been manufactured and sold by the private sector (Box 2). There has been a steady increase in the manufacture and sale of PICS bags for the past 12 years. In the 2018 harvesting season alone, 5.3 million bags were sold globally. This brought the total bags sold globally to 20 million by June 2019. This demonstrates that it is possible to scale up agricultural technologies among smallholder farmers by working with government and development agencies, NGOs, and the private sector. The PICS bag business is entering a transition phase from a project-supported supply chain development to a fully private-sector driven one. PICS Global, a private start-up company, is now working with licensed manufacturers and distributors to expand PICS bag markets in new and existing countries.

Box 2: The private sector is driving the commercialization of PICS bags because the business is viable



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After more than 12 years, the adoption of the PICS technology has resulted in great achievements (Box 3). The key to PICS success is that, since its earliest days, Purdue researchers have worked hand-in-hand with farmers who use the bags every day – making steady and informed improvements. The bags are produced at the cost of about US$1.00 to US$1.50 and are often sold to farmers at US$2.00 to US$3.00. Through investments to reduce storage losses, farmers and the public, in general, have been the biggest beneficiaries of the PICS technology. With sales of 20 million PICS bags, farmers have made or saved more than US$1.5 billion (estimates based on a cash flow of US$25 per 100 kg bag, and each bag is used three times). The private sector, including manufacturers, distributors, and vendors, makes a profit that is sufficient to keep its interest in the business, but small compared to what farmers earn. With a margin of about US$1 for the supply chain, the private sector has made more than US$20 million on the 20 million PICS bags produced and sold to farmers and other users. The PICS program demonstrated that there is a substantial market for hermetic storage technologies among smallholder farmers leading to competition – several brands of hermetic bags were developed and are being sold to farmers in SSA. Other benefits of using PICS and other hermetic bags include the reduction in deaths and illness due to the misuse of insecticides and the mitigation of mold growth (leading to aflatoxin accumulation) that causes stunted growth in children and liver cancer. The later benefits are immeasurable as farmers often tell us, '*There is no price to life*'.

Box 3: Achievement in commercializing PICS bags in sub-Saharan Africa and Asia

- More than 7 million farmers trained to use PICS bags properly.
- More than 65 000 villages reached with training activities.
- More than 10 000 extension/field agents trained.
- Women's participation: 25% of trainers and 40% of trainees.
- 35 countries have PICS activities, and the interest continues to grow around the world.
- 23 licensed local private companies leading PICS commercialization worldwide.
- More than 20 million PICS bags sold from 2007 to June 2019.
- More than 2000 vendors selling PICS bags to farmers.
- US$1.5 billion made or saved by smallholder farmers using PICS bags to store grains.

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7 Summary and future trends

For the past several years, the use of hermetic bags has proven its impact on food safety and security in developing countries. The demand from smallholder farmers for this technology tremendously increased over the past 12 years, and its distribution has increased to more than 35 countries in SSA (mainly) and Asia. There are different types of hermetic bags (single-, double-, and triple bags) commercially available to smallholder farmers that are chemical-free, of low cost, and easy to use. The dissemination of hermetic bags has been implemented by research institutions, non-government organizations, and government agencies to demonstrate the technology and develop sustainable supply chains. These efforts have generated positive results and responses from farmers, and also generated new issues to be addressed.

One of the major issues raised by farmers is the unavaibility of hermetic bags in villages and rural markets. It is important to note that market penetrations differ among hermetic bag brands. Last-mile distribution remains a challenge, and sales are significantly below the potential in each country. There is a need to explore innovative solutions to improve the availability of hermetic bags in rural areas, including the use of Information and Communication Technology (ICT- e.g. sms and USSD) and youth retail models. Hermetic technology has proven to be effective in preventing insect-caused storage losses to cereal and legume crops. Because hermetic bags are manufactured using raw materials from a variety of sources and of varying quality, involve new manufacturers, are deployed in new geographic regions, are used to store a wide range of crops (some of which have not been tested yet), and are adopted by users from different cultures, we anticipate some issues to arise with respect to the performance of the technology. These issues, if left unresolved, might hinder the acceptance and adoption of hermetic bags. Understanding the material properties of the plastic liner used could provide solutions to improving the durability and usability of the technology. The adoption of national, regional, and international standards will contribute to better product consistency and quality control. It is also important to point out that drying practices and moisture assessment are vital operations in ensuring that grains and other stored products are at a safe moisture content before being placed into hermetic bags. Lastly, studying the behavior of farmers in using hermetic bags could help in the design of extension programs to increase adoption.

The impacts of hermetic bags on food security are well established, but there are still many gaps and questions that need to be addressed. More research is needed to improve and expand the supply chain of the hermetic bag to ensure its availability to farmers in rural areas. With large-scale users getting interested in hermetic bags – Could the sealing of bags be automated?

As more governments are banning the use of plastic – Can biodegradable plastic be used to produce hermetic bags? Understanding and comparing the properties and efficacy of single-, double-, and triple-layer bags will be important in developing standards for hermetic bags. Also, full economic and environmental impact assessments would be useful for hermetic bag technology to help governments make evidence-based decisions on plastic bans.

8 Where to look for further information

Several resources are available online:

- *How to properly use hermetic bags for grain storage:* Posters were developed in English and French, and translated into more than 20 local and international languages including Spanish, Swahili, Creole, Djoula, Yoruba, Igbo, Hausa, Chichewa, Tumbuka, Oromiffa, Amharic, Nepali, Kanuri, Hindi, Zarma, Somali, Wolof, Ateso, Kumam, and Twi. These posters are printed and given to farmers, extension agents and vendors. The posters are available online at: https://picsnetwork.org/resources/?tab_id=Posters.
- *How to use hermetic technologies for seed storage:* A poster describing how to use PICS bags and other hermetic containers such as jerrycans and water bottles for seed storage is available online at: https://picsnetwork.org//wp-content/uploads/2018/03/Seed-Storage-Poster-FINAL-reduced-size.pdf.
- *Where to find vendors of PICS bags:* Efforts have been made to make vendors' information available online to facilitate the linkage between potential users and the private sector. A map with pinpoints containing information of manufacturers, distributors and vendors in some of the PICS countries can be found online at: https://picsnetwork.org/where-we-work/?tab_id=distributor.

The following are the resources where information for commercially available hermetic bags in SSA is available:

- AgroZ bag – https://postharvest.nri.org/images/documents/Agroz_bags/AgroZ-bags.pdf.
- ELITE bag – http://eliteinnovations.co.ke/.
- Purdue Improved Crop Storage (PICS) bag – https://picsnetwork.org/.
- SuperGrainbag – https://grainpro.com/what-we-offer/.
- Zerofly bag – https://vestergaard.com/zerofly-hermetic-storage-bag.

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