

Purdue Improved Crop Storage (PICS) Bags: An Innovative Hermetic Storage Technology for Postharvest Crop Management in Developing Countries

Oyewole O. S. ¹; Abdulbaki, M. K. ²; Adisa, A. A. ²; Adebisi, A. O. ³; Raji, M. A. ²; Balogun, B. ²; Ajao, T. O. ¹; Ibitoye O. ²; and Aremu, M. B. ²

¹Postharvest Engineering Research Department, Nigerian Stored Products Research Institute, P.M.B 5044, Ibadan, Nigeria. ²Durable Crops Research Department, Nigerian Stored Products Research Institute, P.M.B 5044 Ibadan, Nigeria. ³Postharvest Engineering Research Department, Nigerian Stored Products Research Institute, P.M.B 1489 Ilorin, Nigeria.

Corresponding author: oyewoleos@nspri.gov.ng

DOI: <https://doi.org/10.62154/ajasfr.2025.020.01016>

Abstract

Postharvest losses remain a major barrier to food security and economic growth in developing countries, where smallholder farmers often lack access to effective crop storage solutions. The Purdue Improved Crop Storage (PICS) bag, developed by Purdue University, is a triple-layer hermetic storage technology designed to reduce such losses without the use of chemical pesticides. This review examines the design, functionality and impact of PICS bags, with a focus on their role in mitigating postharvest losses, improving grain quality, and enhancing the livelihoods of smallholder farmers. It synthesizes peer-reviewed articles, technical reports, and research articles published between 2000 and 2025, identified through systematic searches in Scopus, Web of Science, PubMed, Google Scholar, and relevant organizational websites. Thematic analysis revealed that PICS bags consistently outperformed traditional storage methods, metal silos, polypropylene sacks, and other hermetic storage by controlling insect pests (up to 99% reduction), preventing mold growth, reducing postharvest losses and preserving grain quality for six months or more without chemical application. Evidence also showed positive economic impacts through higher off-season grain prices and reduced pesticide costs, alongside environmental and food safety benefits. However, persistent challenges include low farmer awareness, initial purchase cost, and concerns over durability. This review concludes that, with adequate awareness campaigns, affordability strategies, and continuous technical improvements, PICS bag technology offers a scalable and sustainable solution to postharvest challenges, contributing meaningfully to poverty reduction, food security, and agricultural resilience in vulnerable regions.

Keywords: PICS Bag, Chemical-Free Storage, Triple Layer Bag, Pest Control, Postharvest Losses.

Introduction

Postharvest losses are among the most critical challenges facing global agriculture, particularly in sub-Saharan Africa and other developing countries where smallholder farmers dominate food production. These losses, often caused by pests, poor storage

facilities, and suboptimal handling practices, can reach as high as 40% in cereals and legumes (Affognon et al., 2015). Such losses exacerbate food insecurity, diminish farmer incomes, and hinder sustainable agricultural development. Traditional storage systems such as woven polypropylene bags, open air storage and clay pots offer limited protection which are often leads to loss of grains to pests and mold as a result of poor storage practices. Meanwhile improved solutions like metal silos are often too costly and impractical for small holder farmers.

However, hermetic storage technologies, particularly the Purdue Improved Crop Storage (PICS) bag, have demonstrated strong potential to address these challenges by providing a chemical-free, cost-effective, and scalable solution (Jia & McNamara, 2024). Meanwhile, adoption barriers such as limited awareness, affordability, and concerns about durability persist, and there is a need for comprehensive evidence on their performance across diverse crops, environments, and socio-economic contexts. This review responds to that need by critically examining the design, functionality, and broader impacts of PICS bags to determine their effectiveness in reducing postharvest losses and improving farmer resilience.

PICS bags, developed at Purdue University, offer an innovative hermetic storage system designed to minimize postharvest losses without the use of chemical treatments. The triple-layer technology comprises two polyethylene liners enclosed within a woven polypropylene outer bag (Kunreddy et al., 2023). This design creates an oxygen-deprived environment that effectively limits the survival and reproduction of insect pests, such as weevils and other storage insects, thereby preserving grain quality and quantity (Murdock et al., 2012). Initially targeted at cowpea farmers in West Africa, the technology has since expanded to a wide range of grains, including maize, sorghum, millet, and rice (Martin et al., 2015). The use of PICS bags aligns with broader global goals for sustainable development, particularly the reduction of hunger and promotion of sustainable agricultural practices (Lemaire & Limbourg, 2019). Unlike conventional methods, such as the use of synthetic pesticides or traditional granaries, PICS bags eliminate health risks associated with chemical residues and mitigate environmental pollution (Baoua et al., 2014). Furthermore, the technology empowers smallholder farmers by providing a low cost and scalable storage solution that can enhance food security, market stability, and household incomes (Mvumi & Stathers, 2020).

Despite these advantages, the adoption and efficacy of PICS bags vary across countries and farming systems. Several factors such as cost, availability, farmer awareness, and grain type influence the technology's success. For instance, while PICS bags have proven effective for cowpea storage, challenges remain in their application to grains like maize, which are prone to fungal infections under humid conditions (Mutungi et al., 2015). Addressing these limitations requires comprehensive research and targeted interventions to maximize the utility of PICS bags. This review aims to examine the design, functionality, and operational principles of PICS bags as a hermetic storage technology, evaluate their effectiveness in

reducing postharvest losses, preserving grain quality, and improving the livelihoods of smallholder farmers, and identify the key challenges hindering their widespread adoption while proposing strategies for scaling up their use across diverse crops and farming contexts.

Methodology

This review adopted a narrative synthesis approach with elements of a scoping review, aimed at compiling and thematically analyzing the breadth of available evidence on the Purdue Improved Crop Storage (PICS) bag technology, its role in postharvest crop management, and its wider socio-economic and environmental impacts. A search was performed across multiple academic databases and relevant organizational websites to identify peer-reviewed articles, reports, and other pertinent documents. The primary databases searched including Scopus, Web of Science, PubMed, Google Scholar, and Agricola.

In addition to these academic databases, the websites of key organizations involved in agricultural development and food security, such as the Bill & Melinda Gates Foundation, Purdue University (PICS Project pages), USAID, and various CGIAR centers, were manually searched for relevant reports and publications. The search was conducted between June 2023 and July 2025, encompassing literature published from 2000 (to capture early developments and foundational research) up to 2025.

The following keywords and Boolean operators were used in various combinations to maximize the retrieval of relevant studies: ("PICS bags" OR "Purdue Improved Crop Storage" OR "hermetic storage" OR "hermetic bag" OR "airtight storage") AND ("postharvest loss" OR "crop loss" OR "grain storage" OR "food security" OR "pest control" OR "insect control" OR "fungal control" OR "mycotoxin") AND ("smallholder" OR "farmer" OR "developing countries" OR "Sub-Saharan Africa" OR "South Asia")

Data from the selected documents were systematically extracted and synthesized to address the objectives of this review. Given the diverse nature of the included literature (ranging from empirical field trials to socio-economic assessments), a narrative synthesis approach was primarily employed. Findings were grouped thematically according to the main sections of this review (e.g., technological aspects, economic impact, social dimensions, and future prospect).

Development and Scaling of PICS Bag Technology

The Purdue Improved Crop Storage (PICS) project was initiated by Purdue University with funding from the Bill & Melinda Gates Foundation and other global donors and it has played a pivotal role in addressing postharvest losses in sub-Saharan Africa and other developing countries (Stathers & Mvumi, 2020). The project primarily aims to provide smallholder farmers with an affordable, effective storage solution that reduces postharvest losses caused by pests, moisture, and fungal contamination, thus improving food security and

enhancing the economic stability of farmers (Mompremier et al., 2022). The project undergone through 3 developmental phases.

PICS1: The Initial Phase (2007-2014)

The first phase of the PICS project, known as **PICS1** (Purdue Improved Cowpea Storage), focused on improving cowpea storage in West and Central Africa. Cowpea plays a vital role in food security and income generation in the region, but its storage is often hindered by pests such as weevils. PICS1 aimed to develop a low-cost, chemical-free storage solution to prevent pest infestation without the need for harmful pesticides (Nouhoheflin et al., 2017). During this phase, the PICS bag, a triple-layer storage bag with two inner polyethylene liners enclosed in a woven polypropylene sack, was introduced. This design creates a hermetic environment that deprives pests of oxygen, thus preventing their survival and reproduction (Baributsa et al., 2014). The success of PICS1 was evident in its significant impact on farmer incomes and regional food security. By 2014, the project had successfully reached 1.7 million households, generating an additional \$255 million in income through reduced postharvest losses (Omotilewa & Baributsa, 2022).

PICS2: Expanding Beyond Cowpea (2011-2014)

The second phase of the project, **PICS2** (renamed Purdue Improved Crop Storage), was launched to expand the use of PICS bags beyond cowpea to include other staple crops such as sorghum, rice, maize, and beans. PICS2 emphasized research on the broader applications of the technology, focusing on its effectiveness in controlling mold growth, mycotoxins, and preserving seed viability (Lowenberg-DeBoer and Musa, 2017). Additionally, the phase aimed to evaluate the cost-effectiveness of the PICS bags in improving food security and farmers' livelihoods across different crop types (Muriuki et al., 2016; Kefale et al., 2022). Key research conducted during this phase demonstrated that the bags effectively prevented both insect damage and mold growth, including the mycotoxins that are often present in grains stored under poor conditions (Mutungi et al., 2015). This phase of the project contributed significantly to the adoption of PICS bags by farmers, further solidifying the technology's role as a sustainable solution for postharvest management.

PICS3: Scaling Up and Enhancing Food Security (2015-Present)

The **PICS3** phase marked a more expansive focus on improving market access and food security for smallholder farmers, particularly in Sub-Saharan Africa. This phase sought to increase the adoption of hermetic storage technologies, including PICS bags, by 20%, with the goal of further reducing postharvest losses and increasing farmers' income. The project aimed to reach at least 14,000 villages and ensure that farmers had better access to information and training on the use of hermetic technologies (Baributsa et al., 2019). In addition to the ongoing training programs for farmers, PICS3 also worked on developing a

sustainable supply chain for PICS bags, ensuring their availability in even the most remote areas. The project leveraged mobile phones, radio, and SMS technology to increase awareness and promote the use of PICS bags, especially in countries where traditional communication methods were less effective (Purdue University, 2020). Between 2014 and 2020, the PICS₃ project sold over 19 million bags and reached farmers in more than 40,000 villages across Sub-Saharan Africa. Countries such as Nigeria, Ghana, Ethiopia, Tanzania, Uganda, and Malawi have been key countries where PICS bags are in widespread use (Aker et al., 2023).

Overall Goals, Reach, and Impact of PICS Bags

The PICS project is aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty) and SDG 2 (Zero Hunger) (Lile et al., 2023). By reducing postharvest losses and providing a low-cost, scalable solution for grain storage, the project helps alleviate poverty by increasing farmer incomes and improving food security. Furthermore, the project supports sustainable agriculture by reducing the need for harmful chemical pesticides and enhancing farmers' capacity to preserve their crops for longer periods (Lykogianni et al., 2021).

Since its inception, the PICS project has had a far-reaching impact, helping millions of smallholder farmers improve their storage practices and reduce crop losses (Adams et al., 2024). The PICS₃ program originally focused on seven countries: Nigeria, Ghana, Burkina Faso, Ethiopia, Tanzania, Uganda and Malawi (Clarkson et al., 2022). Now, more than 23 countries in all parts of Africa and even South Asia buy PICS bags. Additionally, PICS bags are in use in more than 40,000 villages in sub-Saharan Africa and more than 2 million farmers have received training on how to use the bags. Between 2014 to March 2020, the project sold more than 19 million PICS bags (Baributsa et al., 2020).

Technological Design of PICS Bags

Overview of PICS Bags Design and Materials

The Purdue Improved Crop Storage (PICS) bags are designed to provide a simple yet highly effective solution for reducing postharvest losses in agricultural produce, particularly grains. PICS bags are constructed with three layers: an inner liner of high-density polyethylene (HDPE), an outer woven polypropylene (PP) bag, and an additional outer liner of polyethylene (Saha et al., 2022). This unique design creates an airtight, oxygen-free environment inside the bag, which prevents insect pests from thriving (Oyewole et al., 2025).

The triple-layer system works by sealing the grain in a protective environment, which significantly limits oxygen availability and disrupts the life cycle of pests such as weevils, beetles, and other storage insects (Hashim et al., 2022). This system also prevents the entry of moisture and contaminants that could otherwise affect grain quality.

Hermetic Sealing and Mechanism of Action in Pest Control

The hermetic sealing mechanism is the primary functional aspect of PICS bags. These bags are designed to create an airtight environment once sealed, trapping gases and moisture inside. This unique feature is the basis for their effectiveness in pest control and grain preservation. The triple-layered construction of PICS bags ensures their effectiveness in maintaining the hermetic environment (Baributsa et al., 2020). The inner layer is specially designed to prevent any leakage, while the outer layers provide additional durability. This robust design ensures that the contents remain in a low-oxygen environment for extended periods. By significantly reducing the oxygen levels within the bag, an anaerobic environment is established, which is inhospitable to most storage pests (Deressa et al., 2025). This process disrupts the normal life cycle of pests by preventing their survival and reproduction (Isman, 2019). Studies have also shown that oxygen levels inside sealed PICS bags drop to as low as 1-2% within a few days, while carbon dioxide levels rise to lethal levels for pests (Baoua et al., 2014). Also,

Hermetic bags are as effective as and sometimes better than insecticides in reducing storage losses due to insects (Baoua et al., 2012a; De-Groote et al., 2013; Mutambuki et al., 2019; Baributsa & Njoroge, 2020). According to Murdock et al. (2012), the absence of oxygen suffocates adult insects, larvae, and eggs, effectively eliminating pests and preventing further damage to stored grains. Studies has shown that 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). Research has demonstrated that PICS bags can reduce pest infestations by up to 90% compared to traditional storage methods, including woven bags and metallic silos (Kuyu et al., 2022; Deressa et al., 2025).

PICS Performance Metrics and Alternative Storage Technologies

Postharvest losses remain a significant challenge in agricultural sectors, particularly in developing countries, where limited infrastructure and resources hinder effective crop storage (Kaur & Watson, 2024). To combat this, various storage technologies have been introduced, including PICS bags, metal silos, polypropylene bags, hermetic containers, and traditional storage methods.

PICS Performance Metrics

Smallholder farmers, especially those in developing countries with limited access to advanced storage technologies, benefit greatly from PICS bags. Traditional storage methods, such as open-air storage or crude containers, are ineffective at protecting crops from pests, environmental factors, and microbial contamination. PICS bags offer a cost-

effective, easy-to-use alternative that does not require special equipment or training. They provide a solution for farmers to store crops for extended periods without the need for chemical preservatives or refrigeration, which are often unavailable or too costly (Mandal et al., 2024).

Several researches have shown diverse efficacy of PICS bags (Table 1). Sanon et al. (2011) evaluated the efficacy of triple-bagging cowpeas using heavy-grade high-density polyethylene (HDPE) against *Callosobruchus maculatus*, the primary storage pest of *Vigna unguiculata* in West Africa. Laboratory trials demonstrated that using two HDPE layers of at least 80 µm wall thickness significantly reduced oxygen concentrations within five days, thereby inhibiting insect development and reducing seed damage. On-farm trials, where two HDPE bags (50 kg capacity) were tightly sealed and enclosed in a woven nylon sack, maintained protection for seven months, with seed damage remaining below 7% and germination rates above 89%. The results confirm that triple-bagging with locally available materials offers an affordable, effective, and long-term storage method that preserves cowpea quality and viability while minimizing pest damage.

Baoua et al. (2014a) investigated the suitability of Purdue Improved Crop Storage (PICS) triple-layer bags, originally designed for cowpea, for maize storage in West Africa, where postharvest losses can reach 30% due to pests. Trials were conducted in 2012 across eleven localities in Benin, Burkina Faso, and Ghana, using naturally infested or lightly infested maize stored for 6.5 months in PICS and woven polypropylene control bags. The PICS bags achieved 95–100% insect mortality for *Prostephanus truncatus*, *Sitophilus zeamais*, and *Rhyzopertha dominica*, while maintaining seed weight, damage levels, and germination rates equivalent to initial values.

Njoroge et al. (2014) examined the effectiveness of triple-layer hermetic Purdue Improved Crop Storage (PICS™) bags against *Prostephanus truncatus* in stored maize under ambient conditions for six months. Clean shelled maize was stored in either woven polypropylene (PP) or PICS bags, with (PP₁, PICS₁) or without (PP₀, PICS₀) initial infestation. Monthly assessments included moisture content, live insect population, grain damage, weight loss, germination, and, for PICS bags, internal temperature, relative humidity, oxygen, and carbon dioxide levels. Results showed that PICS storage maintained significantly lower moisture content and prevented cross-infestation, while Polypropylene bags (PP) allowed rapid insect proliferation. After six months, grain damage and weight loss were 0.0% and 0.0% in PICS₀, 3.4% and 2.0% in PICS₁, compared to 50.5% and 36.3% in PP₀, and 73.9% and 47.7% in PP₁. Germination remained high in PICS (78.1% in PICS₀; 71.0% in PICS₁) but declined sharply in PP (37.0% in PP₀; 12.7% in PP₁). The study concludes that PICS bags effectively suppress *P. truncatus* populations, protect grain quality, and maintain viability without chemical use, even under endemic pest conditions.

Ng'ang'a et al. (2016) conducted participatory on-farm trials in eastern Kenya to evaluate the effectiveness of Purdue Improved Crop Storage (PICS™) bags in preventing maize losses under small-scale farmer storage conditions. Shelled maize was stored for 35 weeks in jute, woven polypropylene, or triple-layer PICS bags within farmers' stores. PICS bags

maintained stable moisture content and demonstrated strong air-barrier properties, while maize in polypropylene and jute bags experienced significant moisture loss in the final 14 weeks. No insect infestation occurred in PICS bags, and weight loss from insect damage remained below 1%, compared to heavy infestation in polypropylene and jute bags, which suffered grains damage of 77.6% and 82.3% and weight losses of 41.2% and 48.5%, respectively. The results confirm PICS bags as an effective technology for controlling storage pest losses in rural on-farm conditions.

Kharel et al. (2018) investigated alternative sealing methods for Purdue Improved Crop Storage (PICS) bags, which are conventionally closed using the twist-tie (TT) method, a process that is time-consuming and may weaken the liners. Four sealing methods: TT, inner rolled (IR), fold-together (FT), and fold-separate (FS) were tested on 50 kg maize-filled bags under varying levels of *Sitophilus zeamais* infestation. The FT method reduced sealing time by over 34% compared to TT, while oxygen depletion patterns (<2% in heavily infested grain within a week) and insect suppression remained consistent across all methods. The findings demonstrate that FT offers a labor-saving, large-scale sealing alternative without compromising PICS bag storage efficacy.

Waongo et al. (2019) evaluated the performance of Purdue Improved Crop Storage (PICS) bags for long-term sorghum (*Sorghum bicolor*) preservation under ambient conditions in Burkina Faso. Batches of 25 kg of sorghum were stored in 50 kg PICS or polypropylene (PP) bags for 12 months and monitored for insect pest presence, grain damage, weight loss, seed viability, and changes in oxygen and carbon dioxide levels. Oxygen declined in PICS bags after six months, while PP bags maintained ambient levels. After 12 months, only *Rhyzopertha dominica* and *Sitophilus zeamais* were detected in PICS bags, whereas PP bags also contained *Tribolium castaneum*, *Oryzaephilus mercator*, and *Xylocoris flavipes*. Grain damage and weight loss were significantly higher in PP bags, and germination rates in PP-stored grain declined markedly, while PICS-stored grain retained initial viability. A post-storage incubation revealed some resurgence of *R. dominica* in PICS grain, though at much lower levels than in PP grain. The study concludes that PICS technology effectively preserves sorghum quality and viability for long-term storage, though the potential for low-level pest resurgence in hermetic conditions warrants further investigation.

Mutambuki et al. (2019) conducted an on-station evaluation of triple-layer Purdue Improved Crop Storage (PICS) hermetic bags against *Prostephanus truncatus* and *Sitophilus zeamais*, two major maize storage pests. Fifty-kilogram batches of maize were stored in PICS, jute, and polypropylene bags, with some jute and polypropylene bags treated with Pirimiphos methyl (1.6%) and Permethrin (0.3%) as positive controls. One set of PICS bags was artificially infested with both pest species, while another was not. Gas monitoring in PICS bags showed a rapid oxygen decline to below 10% and carbon dioxide increase to about 10% within 12 weeks, leading to pest mortality. After 16 weeks, a slight oxygen increase was attributed to external perforation by *P. truncatus*. After 24 weeks, weight loss in polypropylene and jute bags reached 40–41%, compared to only 2.4–2.9% in PICS bags.

The study demonstrated that PICS bags were significantly more effective ($P < 0.05$) than both treated and untreated conventional bags in suppressing insect development, preventing grain damage, and minimizing weight loss, confirming their suitability for protecting maize against major storage pests without reliance on chemical insecticides.

Table 1. Comparative efficacy of PICS bags in with other alternative storage methods

Author & Year	Crop Studied	Target Pest(s)	Storage Duration	Storage Method	Key Findings
Sanon et al. (2011)	Cowpea (<i>Vigna unguiculata</i>)	<i>Callosobruchus maculatus</i>	7 months (on-farm); lab trials	Triple-bagging with 2 HDPE liners + woven sack	O ₂ reduced within 5 days, inhibiting insect development. Damage <7%, germination >89%. Effective long-term protection.
Baoua et al. (2014)	Maize	<i>Prostephanus truncatus</i> , <i>Sitophilus zeamais</i> , <i>Rhyzopertha dominica</i>	6.5 months	PICS vs. woven PP	95–100% insect mortality, preserved seed weight & germination. Lower aflatoxin in PICS-stored maize.
Njoroge et al. (2014)	Maize	<i>Prostephanus truncatus</i>	6 months	PICS vs. woven PP (with/without infestation)	PICS prevented cross-infestation, 0–3.4% damage vs. 50–74% in PP. Germination 71–78% (PICS) vs. 13–37% (PP).
Ng'ang'a et al. (2016)	Maize	Mixed storage pests	35 weeks (~8 months)	Jute, PP, vs. PICS	PICS maintained stable moisture, no infestation, <1% weight loss vs. 41–49% in PP/jute. Damage: 0% (PICS) vs. 78–82% (PP/jute).
Kharel et al. (2018)	Maize	<i>Sitophilus zeamais</i>	Short-term (O ₂ test up to 1 week)	PICS sealed with 4 methods (TT, IR, FT, FS)	FT sealing reduced time by 34% with same efficacy. O ₂ <2% within a week in infested bags, insect suppression consistent.
Waongo et al. (2019)	Sorghum (<i>Sorghum bicolor</i>)	<i>Rhyzopertha dominica</i> , <i>Sitophilus zeamais</i>	12 months	PICS vs. PP	PICS reduced insect diversity & damage, retained seed viability. Some low-level resurgence of <i>R. dominica</i> .
Mutambuki et al. (2019)	Maize	<i>Prostephanus truncatus</i> , <i>Sitophilus zeamais</i>	24 weeks (~6 months)	PICS vs. jute & PP (treated & untreated)	Rapid O ₂ decline (<10%) & CO ₂ rise (~10%). Weight loss: 2.4–2.9% (PICS) vs. 40–41% (PP/jute). PICS more effective than chemical-treated bags.

PICS: Purdue Improved Crop Storage bag, HDPE: High Density Polythene, PP: Polypropylene, TT: Twist-tie method, IR: Inner rolled Methods, FT: Fold together, FS: Fold separately.

Alternative Storage Technologies

Metal Silos

Metal silos are commonly used in large-scale agricultural operations due to their ability to provide airtight, durable storage, which prevents the infiltration of pests and mold. These silos also help control temperature and humidity, preserving the quality of stored grains over extended periods. According to studies, metal silos have been found to significantly reduce postharvest losses due to insect pests and spoilage (Kongkaew et al., 2017; Nag, 2024). However, the high cost of construction, maintenance, and installation of metal silos makes them less accessible for smallholder farmers in rural areas. Additionally, their size and immobility make them impractical for farmers who need flexible, portable storage solutions (Kolli et al., 2023).

In comparison, PICS bags, which are based on hermetic technology, offer an affordable and portable alternative that is easy to use and requires no significant infrastructure. A study by Baoua et al. (2012) demonstrated that PICS bags provide similar protection against pests and moisture as metal silos but at a fraction of the cost. Their lightweight, portable design makes them particularly well-suited for smallholder farmers who need flexible storage options. Furthermore, PICS bags can be used in diverse climates without the need for electricity or specialized tools, overcoming some of the limitations associated with metal silos (Sugri et al., 2023).

Polypropylene Bags

Polypropylene bags are one of the most commonly used storage methods for grains in developing countries due to their low cost and availability. However, these bags have several limitations, particularly regarding pest control and moisture management. Studies show that polypropylene bags are porous and do not effectively prevent pest infiltration or the development of mold (Mandal et al., 2024). Additionally, the bags do not provide insulation from environmental fluctuations in temperature and humidity, increasing the risk of crop spoilage (Omodara et al., 2020).

PICS bags, in contrast, are designed with an airtight seal that creates a controlled environment within the bag, preventing pests and mold growth. Baoua et al. (2012a) conducted a study comparing PICS bags with polypropylene bags and found that PICS bags reduced pest infestation by 99% compared to traditional polypropylene bags. The multi-layered construction of PICS bags also provides better insulation from external weather conditions, ensuring that the grains remain protected from environmental damage (Okparavero et al., 2024). The airtight technology is particularly beneficial for smallholder

farmers, as it does not require refrigeration or specialized equipment, unlike polypropylene bags, which are often inadequate in preventing spoilage.

Hermetic Storage Containers

Hermetic storage containers are specifically designed to create an airtight environment for storing grains. These containers often made of metal or plastic, offer effective pest control by preventing oxygen exchange, which is essential for the survival of insect pests. Studies on hermetic storage containers have shown that they can significantly reduce postharvest losses from insect infestation (Chigoverah et al., 2014). However, these containers are typically bulkier and more expensive than other options, which limit their accessibility to smallholder farmers in developing countries (Manandhar et al., 2018). Additionally, hermetic containers are less portable and require more storage space, making them less suitable for small-scale or mobile storage (Covele et al., 2020).

PICS bags, in contrast, offer a more affordable and flexible solution. The technology used in PICS bags is based on hermetic storage principles, providing similar protection against pests and mold as larger, bulkier hermetic containers. However, PICS bags are more cost-effective, lightweight, and portable, which makes them a more practical solution for smallholder farmers (Baributsa and Ignacio, 2020). PICS bags have been shown to offer the same level of pest control as hermetic containers, but at a lower cost and with greater convenience (Nwaubani et al., 2020). Additionally, the ease of handling and transportation of PICS bags gives them a significant advantage over hermetic containers in resource-limited settings.

Traditional Methods

Traditional storage methods, such as open-air storage, woven sacks, or clay pots, are still prevalent in many developing countries. These methods are typically low-cost but offer minimal protection against pests, moisture, and environmental stressors (Mobolade et al., 2019). Research has consistently shown that grains stored using traditional methods are highly susceptible to infestation by pests like weevils and rodents and mold growth due to moisture exposure (Ziegler et al., 2021). These methods also do not provide insulation from temperature fluctuations, which can further increase the risk of crop spoilage.

PICS bags offer a significant improvement over these traditional storage methods. The airtight seal in PICS bags creates a controlled environment, significantly reducing the risk of pest infestation and mold growth. In a study by Baoua et al. (2012b), PICS bags were found to reduce the infestation of insect pests by over 90% compared to traditional storage methods. Furthermore, the hermetic technology in PICS bags prevents the entry of moisture, ensuring that stored grains remain dry and free from mold, which is a major concern with traditional methods. The PICS bags also help prevent cross-contamination between different crops, further preserving the quality of stored grains. This makes PICS bags a far superior option for maintaining the quality of grains over traditional methods, ensuring longer-term storage with minimal loss.

Economic Impact of PICS Bags

The economic impact of PICS bags extends well beyond immediate reductions in postharvest losses. A detailed economic model helps illuminate how these bags can improve farmer livelihoods and contribute to regional economic growth over the long term.

Income Stability and Profitability: One of the most significant economic benefits of PICS bags is the reduction in postharvest losses. In countries with limited storage options, losses can reach 30% to 50% of the harvested crop due to pests, mold, or environmental exposure. By reducing these losses, PICS bags allow farmers to retain more of their harvest, directly increasing their available income (Dubey et al., 2024). For example, a study in Niger found that PICS bags reduced postharvest losses of millet by more than 80%, leading to substantial increases in farmer income (Baoua et al., 2012a). This saved produce can be sold at higher prices during the off-season, improving farmers' cash flow and providing a buffer against market price fluctuations. Jones et al. (2011) conducted an economic assessment of the potential for hermetic Purdue Improved Crop Storage (PICS) bags to increase incomes for maize producers in sub-Saharan Africa by reducing storage losses from *Prostephanus truncatus* and *Sitophilus zeamais*. The study integrated dry weight loss data from prior biological research with market price seasonality, value loss prevention, and opportunity costs of capital to model technology adoption potential across Tanzania, Kenya, Malawi, Mozambique, and Ghana. Profitability of PICS bags, with one and two years of use, was compared to Sofagrain (deltamethrin 0.5% + pirimiphos-methyl 1.5%) and Actellic Super (permethrin 0.3% + pirimiphos-methyl 1.6%). Results indicated that PICS technology consistently outperformed insecticides in profitability, with the greatest adoption potential in Malawi, Mozambique, Tanzania, and Ghana. The findings suggest that, beyond its proven pest control efficacy, PICS storage can be a financially attractive investment for market-oriented maize farmers in the region.

Reduction in Pesticide Costs: Another economic benefit is the savings on pest control. Traditional storage methods often rely on chemical pesticides to prevent infestations. However, these chemicals can be expensive, hazardous to human health, and environmentally damaging. PICS bags eliminate the need for pesticides by creating a sealed, oxygen-deprived environment that prevents pests from thriving. This naturally reduces both input costs and the negative health impacts associated with pesticide use (Kumar & Kalita, 2017).

Market Access and Food Security: The ability to store crops for longer periods also opens up opportunities for farmers to better time the sale of their harvest. By holding onto crops until market conditions are favorable (e.g., when prices are higher), farmers can maximize their profits. PICS bags also contribute to food security by reducing spoilage, ensuring that crops are available even during off-seasons or during periods of scarcity (Okori et al., 2022). This ability to store crops improves local food availability and reduces dependency on external sources of food, enhancing resilience against market volatility and climate-related disruptions.

Community Economic Benefits: As more farmers adopt PICS bags, the local economy benefits. Increased agricultural productivity can support local markets, increase employment in agricultural-related industries, and boost regional economies. In addition, as food security improves, public health costs associated with malnutrition and food insecurity are reduced, further contributing to economic stability (Misselhorn et al., 2012).

Global Perspective: The Adoption and Impact of PICS Bags Beyond Africa

While PICS bags have proven highly effective in Africa, their potential in other developing countries cannot be overlooked. The principles behind the technology are applicable to any region that faces challenges in postharvest crop management due to pests, moisture, and spoilage.

In South Asia, countries like India and Bangladesh experience significant postharvest losses, especially in staple crops like rice, wheat, and legumes. In India, postharvest losses for grains like wheat can reach 10-15% (Kumar & Kalita, 2017), while losses for pulses like lentils can be even higher due to inadequate storage conditions. PICS bags have been shown to reduce losses by more than 70% in trials conducted in India, offering a sustainable, low-cost solution to these challenges (Amin et al., 2019). Furthermore, the region faces challenges such as climate change and erratic rainfall, which impact the moisture content of grains during storage. The hermetic properties of PICS bags help mitigate these effects, ensuring that crops remain stable under diverse climatic conditions.

In Southeast Asia, countries like Vietnam and Indonesia also face issues with grain storage, especially with rice and corn. According to the Kumar and Kalita (2017), rice storage losses in Southeast Asia range between 15% and 30%. PICS bags offer a promising solution, reducing storage losses significantly and allowing farmers to store their rice for longer periods. In Indonesia, where smallholder rice farmers dominate, the use of PICS bags has been linked to improved yields and reduced postharvest losses (FAO, 2019). In Latin America, particularly in countries like Guatemala and Honduras, postharvest losses of crops like corn, beans, and coffee are common due to lack of effective storage. In Honduras, grain storage losses due to pests and mold have been estimated at 25% (Odjo et al., 2022). PICS bags could reduce these losses by over 50%, providing a more affordable and accessible alternative to chemical treatments and complex storage systems (Chavez et al., 2020). In countries with humid and tropical climates, such as parts of Central America, moisture control in storage is a major concern. The airtight design of PICS bags helps to regulate moisture, keeping stored crops dry and preventing mold growth (Williams et al., 2017).

Expanding the use of PICS bags beyond Africa has contributed significantly to food security and economic stability in other developing countries. By addressing common storage challenges, PICS bags offer a scalable, adaptable solution for farmers worldwide, reducing postharvest losses and improving livelihoods in vulnerable communities.

Challenges and Limitations of PICS Bags

Despite the demonstrated efficacy and numerous benefits of PICS bags, their widespread adoption and sustained impact are not without challenges and limitations. Addressing these issues is crucial for optimizing their performance and ensuring equitable access and benefits.

Awareness and Education

Despite the benefits of PICS bags, their adoption has been slow in some countries due to limited knowledge about their advantages. Many farmers continue to rely on traditional storage methods because they are unaware of the benefits offered by the PICS bag system. Furthermore, in rural areas, access to agricultural extension services and training programs is often limited, which impedes the dissemination of knowledge about modern storage technologies (Arowosegbe et al., 2024). Extension services play a vital role in educating farmers about the benefits of PICS bags and how to use them effectively. Awareness campaigns and farmer-to-farmer knowledge sharing are essential to improving the adoption rate of these bags (Ndaghu et al., 2023).

Cost Considerations

While PICS bags are relatively inexpensive compared to other storage technologies, the initial cost can still be a barrier for smallholder farmers, especially in low-income countries. The bags' price may vary depending on the size and materials used, but they are generally affordable for most farmers in developing countries (Omotilewa, 2017). Nevertheless, the upfront investment can be a deterrent for those who are unfamiliar with the bags' benefits. Efforts to make the bags more affordable, such as subsidies or partnerships with NGOs, could help increase their adoption. Additionally, farmers need to be educated about the long-term savings and food security benefits of using PICS bags, which can offset the initial cost over time (Martey et al., 2023).

Maintenance and Durability

PICS bags are durable and reusable, but their lifespan depends on proper handling. Farmers need to be trained on how to use and maintain the bags to ensure they continue to perform effectively. Wear and tear, exposure to sunlight, and physical damage can compromise the bags' ability to maintain an airtight seal. Regular checks for damage, proper sealing techniques, and careful handling can help extend the lifespan of the bags. In some cases, farmers may need to replace bags after several uses, adding to the overall cost of the system (Hell et al., 2010). Maintenance practices should be incorporated into extension training programs to ensure that the bags remain functional for as long as possible.

Future Research Directions: Innovations and Improvements in PICS Bag Technology

Material Innovation: Research into the development of more eco-friendly materials for PICS bags is critical. The use of biodegradable or compostable polymers could reduce the environmental impact of plastic waste in rural areas, which is a growing concern (Dilkes et al., 2019). Furthermore, alternative materials could improve the durability and strength of the bags, especially in extreme climates or rough handling conditions.

Active Packaging Technologies: Researchers are exploring the use of active packaging technologies to enhance the functionality of PICS bags. For example, the inclusion of oxygen absorbers or moisture control packets within the bags could further extend the shelf life of stored crops, particularly in countries where crops are prone to moisture-related spoilage. These innovations would improve the ability of PICS bags to store a wider variety of crops, such as root vegetables or fruits that require strict humidity control.

Scalability: As the adoption of PICS bags grows, more attention must be given to scaling the technology for use in larger agricultural operations. Research into the development of bulk storage solutions using PICS bags could address the needs of larger farmers or cooperative groups while maintaining the affordability and ease of use that make the bags so attractive to smallholders. Additionally, expanding the supply chain for the manufacturing and distribution of PICS bags could ensure wider availability.

Conclusion

The Purdue Improved Crop Storage (PICS) bag technology represents a breakthrough in addressing one of the most persistent challenges in agricultural systems of developing countries, postharvest losses. By providing a low-cost, chemical free and scalable hermetic storage solution, PICS bags empower smallholder farmers to preserve grain quality, minimize pest infestations, reduce spoilage, and increase food availability throughout the year. This review has highlighted the multifaceted benefits of PICS bags, including their superior pest control mechanisms, economic advantages, environmental safety and alignment with the Sustainable Development Goals. Comparative analysis has shown that PICS bags outperformed traditional methods and rival more expensive alternatives such as metal silos and hermetic containers, especially in terms of affordability, portability, and accessibility for small-scale farmers. Their use has resulted in substantial reductions in crop losses (upto 80% in some cases) translating into improved household food security, increased income, and better resilience against market and climate shocks.

Despite these significant gains, challenges related to awareness, affordability, maintenance, and availability still hinder widespread adoption, especially in remote or resource-constrained settings. Addressing these barriers through targeted extension services, public-private partnerships, subsidies, and community-based training programs is essential for scaling the technology. Future research and innovation should also focus on enhancing the material sustainability of PICS bags, integrating them with complementary postharvest technologies, and adapting the design for other perishable crops and larger-scale operations.

References

- Adams, F., Donkor, E., Quaye, J., Jantuah, A. A., & Etuah, S. (2024). Sustainable Maize Storage Technology Adoption in Ghana: Implications for Postharvest Losses, Farm Income, and Income Inequality. *Food and Energy Security*, 13(5), e70011. <https://doi.org/10.1002/fes3.70011>
- Affognon, H., Mutungi, C., Sanginga, P., & Borgemeister, C. (2015). Unpacking postharvest losses in sub-Saharan Africa: a meta-analysis. *World development*, 66, 49-68. <https://doi.org/10.1016/j.worlddev.2014.08.002>
- Aker, J. C., Dillon, B., & Welch, C. J. (2023). Demand, supply and long-term adoption: Evidence from a storage technology in West Africa. *Journal of Development Economics*, 165, 103129. <https://doi.org/10.1016/j.jdeveco.2023.103129>
- Arowosegbe, O. B., Alomaja, O. A., & Tihamiyu, B. B. (2024). The role of agricultural extension workers in transforming agricultural supply chains: enhancing innovation, technology adoption, and ethical practices in Nigeria. *World Journal of Advanced Research and Reviews*, 23(3), 2585-2602. <https://doi.org/10.30574/wjarr.2024.23.3.2962>
- Baoua, I. B., Amadou, L., Bakoye, O., Baributsa, D., & Murdock, L. L. (2016). Triple bagging hermetic technology for post-harvest preservation of paddy rice *Oryza sativa* L. in the Sahel of West Africa. *Journal of Stored Products Research*, 68, 73-79. <https://doi.org/10.1016/j.jspr.2016.04.006>
- Baoua, I. B., Amadou, L., Ousmane, B., Baributsa, D., & Murdock, L. L. (2014a). PICS bags for post-harvest storage of maize grain in West Africa. *Journal of Stored Products Research* 58, 20-28. <https://doi.org/10.1016/j.jspr.2014.03.001>.
- Baoua, I. B., Amadou, L., Baributsa, D. & Murdock, L. L. (2014b). Triple bag hermetic technology for post-harvest preservation of Bambara groundnut (*Vigna subterranea* (L.) Verdc.). *Journal of Stored Products Research* 58, 48-52. <https://doi.org/10.1016/j.jspr.2014.01.005>.
- Baoua, I. B., Amadou, L., & Murdock, L. L. (2013). Triple bagging for cowpea storage in rural Niger: Questions farmers ask. *Journal of Stored Products Research*, 52, 86-92. <https://doi.org/10.1016/j.jspr.2012.12.004>
- Baoua, I. B., Margam, V., Amadou, L., & Murdock, L. L. (2012a). Performance of triple bagging hermetic technology for postharvest storage of cowpea grain in Niger. *Journal of Stored Products Research*, 51, 81-85. <https://doi.org/10.1016/j.jspr.2012.07.003>
- Baoua, I. B., Amadou, L., Margam, V. & Murdock, L. L. (2012b). Comparative evaluation of six storage methods for postharvest preservation of cowpea grain. *Journal of Stored Products Research* 49, 171-175. <https://doi.org/10.1016/j.jspr.2012.01.003>
- Baributsa, D. and Njoroge, A. W. (2020). The use and profitability of hermetic technologies for grain storage among smallholder farmers in Eastern Kenya. *Journal of Stored Products Research* 87. <https://doi.org/10.1016/j.jspr.2020.101618>.
- Baributsa, D., & Ignacio, M. C. (2020). Developments in the use of hermetic bags for grain storage. *Burleigh Dodd Series in Agricultural Science*, Pg 1-29. <https://doi.org/10.19103/AS.2020.0072.06>
- Baributsa, D., Lowenberg-DeBoer, J., Murdock, L., & Moussa, B. (2019). Profitable chemical-free cowpea storage technology for smallholder farmers in Africa: opportunities and challenges. *Gates Open Res*, 3(853), 853. <https://doi.org/10.5073/jka.2010.425.340>
- Baributsa, D., Djibo, K., Lowenberg-DeBoer, J., Moussa, B., & Baoua, I. (2014). The fate of triple-layer plastic bags used for cowpea storage. *Journal of stored products research*, 58, 97-102. <https://doi.org/10.1016/j.jspr.2014.02.011>
- Chigoverah, A. A., Mvumi, B. M., Kebede, A. T., & Tefera, T. (2014, November). Effect of hermetic facilities on stored maize insect infestation and grain quality. In *Proceedings of 11th International Working Conference on Stored Product Protection November* (pp. 24-28). <https://doi.org/10.14455/DOA.res.2014.62>

- Clarkson, G., Dorward, P., Poskitt, S., Stern, R. D., Nyirongo, D., Fara, K., & Giraldo, D. (2022). Stimulating small-scale farmer innovation and adaptation with Participatory Integrated Climate Services for Agriculture (PICSA): Lessons from successful implementation in Africa, Latin America, the Caribbean and South Asia. *Climate Services*, 26, 100298. <https://doi.org/10.1016/j.cliser.2022.100298>
- Covele, G., Gulube, A., Tivana, L., Ribeiro-Barros, A. I., Carvalho, M. O., Ndayiragije, A., & Nguenha, R. (2020). Effectiveness of hermetic containers in controlling paddy rice (*Oryza sativa* L.) storage insect pests. *Journal of Stored Products Research*, 89, 101710. <https://doi.org/10.1016/j.jspr.2020.101710>
- De Groote, H., Kimenju, S. C., Likhayo, P., Kanampiu, F., Tefera, T. & Hellin, J. (2013). Effectiveness of hermetic systems in controlling maize storage pests in Kenya. *Journal of Stored Products Research* 53, 27–36. <https://doi.org/10.1016/j.jspr.2013.01.001>
- Deressa, T., Diro, D., Getachew, G., & Demissie, G. (2025). Performance Evaluation of Metal Silo and PICS bag for Maize Grain Storage against Insect Pest Infestation and Grain Quality. *EAS Journal of Nutrition and Food Sciences*, 7(1), 1-9. <https://doi.org/10.36349/easjnfs.2025.v07i01.001>
- Dubey, A., Mani, I., Routray, W., Nebapure, S. M., & Parray, R. A. (2024). Evaluating bag storage technologies for physical characteristics, loss reduction and economic viability in pulses. *Journal of Stored Products Research*, 107, 102339. <https://doi.org/10.1016/j.jspr.2024.102339>
- Guenha, R., Salvador, BdV., Rickman, J., Goulaoc, L. F., Muochaa, I. M. & Carvalho, M. O. (2014). Hermetic storage with plastic sealing to reduce insect infestation and secure paddy seed quality: a powerful strategy for rice farmers in Mozambique. *Journal of Stored Products Research* 59, 275–281. <https://doi.org/10.1016/j.jspr.2014.06.007>.
- Hashim, N., Onwude, D. I., & Maringgal, B. (2022). Technological advances in postharvest management of food grains. *Research and Technological Advances in Food Science*, 371-406. <https://doi.org/10.1016/B978-0-12-824369-5.00016-6>
- Hell, K., Ognakossan, K. E., Tonou, A. K., Lamboni, Y., Adabe, K. E., & Coulibaly, O. (2010, September). Maize stored pests control by PICS-bags: technological and economic evaluation. In *Presentation at the 5th World Cowpea Conference, Saly, Senegal*, 27, 335-342.
- Ignacio, M. C. C. D., Rosentrater, K. A., & Maier, D. E. (2023). Estimating environmental and economic impacts of hermetic bag storage technology. *Sustainability*, 15(20), 14850. <https://doi.org/10.3390/su152014850>
- Jones, M., Alexander, C., & Lowenberg-DeBoer, J. (2014). A simple methodology for measuring profitability of on-farm storage pest management in developing countries. *Journal of Stored Products Research*, 58, 67-76. <https://doi.org/10.1016/j.jspr.2013.12.006>
- Isman, M. B. (2019). Challenges of pest management in the twenty first century: new tools and strategies to combat old and new foes alike. *Frontiers in Agronomy*, 1, 2. <https://doi.org/10.3389/fagro.2019.00002>
- Jia, J., & McNamara, P. E. (2024). Information interventions and willingness to pay for PICS bags: Evidence from Sierra Leone. *Food Policy*, 129, 102760. <https://doi.org/10.1016/j.foodpol.2024.102760>
- Jones, M., Alexander, C., & Lowenberg-DeBoer, J. (2011). An initial investigation of the potential for hermetic Purdue improved crop storage (PICS) bags to improve incomes for maize producers in Sub-Saharan Africa. *Department of Agric Economics, Purdue University*.
- Kaur, R., & Watson, J. A. (2024). A scoping review of postharvest losses, supply chain management, and technology: implications for produce quality in developing countries. *Journal of the ASABE*, 67(5), 1103-1131. <https://doi.org/10.13031/ja.15660>
- Kefale, T., Ayalew, Z., Birhanie, Z., Wubetie, B. Y., & Baributsa, D. (2022). Cost-benefit analysis of Purdue Improved Crop Storage bags for maize storage among smallholder farmers in northwest Ethiopia. *African Journal of Food, Agriculture, Nutrition and Development*, 22(9), 21672-21693. <https://doi.org/10.18697/ajfand.114.22100>

- Kharel, K., Mason, L. J., Williams, S. B., Murdock, L. L., Baoua, I. B., & Baributsa, D. (2018). A time-saving method for sealing Purdue Improved Crop Storage (PICS) bags. *Journal of stored products research*, 77, 106-111. <https://doi.org/10.1016/j.jspr.2018.04.002>
- Kolli, V. S., Garg, S., & Shirkole, S. S. (2023). Silos and bins. In *Transporting Operations of Food Materials Within Food Factories* (pp. 61-93). Woodhead Publishing. <https://doi.org/10.1016/B978-0-12-818585-8.00009-X>
- Kongkaew, N., Srimitrungroj, T., & Kerdsuwan, S. (2017). The Metal Silo: An Effective Grain Storage Technology for Reducing Post-Harvest Losses in Paddy Storage. *Key Engineering Materials*, 728, 353-358. <https://doi.org/10.4028/www.scientific.net/KEM.728.353>
- Kumar, D., & Kalita, P. (2017). Reducing postharvest losses during storage of grain crops to strengthen food security in developing countries. *Foods*, 6(1), 8. <https://doi.org/10.3390/foods6010008>
- Kunreddy, M. R., Pidigam, S., Sudini, H., Amarapalli, G., Komatireddy, R. R., & Margam, V. (2023). Triple layer hermetic bags for safe storage of dry Chilli (*Capsicum annuum* L.) pods. *Journal of Food Science and Technology*, 60(7), 1970-1980. <https://doi.org/10.1007/s13197-023-05731-1>
- Kuyu, C. G., Tola, Y. B., Mohammed, A., Mengesh, A., & Mpagalile, J. J. (2022). Evaluation of different grain storage technologies against storage insect pests over an extended storage time. *Journal of Stored Products Research*, 96, 101945. <https://doi.org/10.1016/j.jspr.2022.101945>
- Lemaire, A., & Limbourg, S. (2019). How can food loss and waste management achieve sustainable development goals? *Journal of cleaner production*, 234, 1221-1234. <https://doi.org/10.1016/j.jclepro.2019.06.226>
- Lile, R., Oclean, M., Balan, I. M., & KIBA, D. (2023). Challenges for Zero Hunger (SDG 2): Links with Other SDGs. *Transitioning to Zero Hunger. Chapter*, MDPI, 9-66. <https://doi.org/10.3390/books978-3-03897-863-3>
- Lowenberg-DeBoer, J., & Musa, S. (2017). University Licensing Of Intellectual Property In Developing Countries: A Case Study Of The Purdue Improved Crop Storage (Pics) Technology. *Department of Agricultural economics, Purdue University*. <https://doi.org/10.22004/ag.econ.254126>
- Lykogianni, M., Bempelou, E., Karamaouna, F., & Aliferis, K. A. (2021). Do pesticides promote or hinder sustainability in agriculture? The challenge of sustainable use of pesticides in modern agriculture. *Science of the Total Environment*, 795, 148625. <https://doi.org/10.1016/j.scitotenv.2021.148625>
- Manandhar, A., Milindi, P., & Shah, A. (2018). An overview of the post-harvest grain storage practices of smallholder farmers in developing countries. *Agriculture*, 8(4), 57. <https://doi.org/10.3390/agriculture8040057>
- Mandal, S., Kalakandan, S. K., & Sugumar, A. (2024). Effective packaging and handling of food grains for quality and safety management. In *Unit Operations in Food Grain Processing*, 513-546. Academic Press. <https://doi.org/10.1016/B978-0-443-18965-4.00018-2>
- Mann, S., Balakrishnan, R., Mohapatra, S., & Kotwaliwale, N. (2025). On-Farm Processing and Marketing Models for Farmers of Developing Countries. In *2025 ASABE Annual International Meeting* (p. 1). American Society of Agricultural and Biological Engineers. <https://doi.org/10.13031/aim.202500371>
- Martey, E., Etwire, P. M., Suraj, M. M., & Goldsmith, P. (2023). PICS or poly sack: Traders' willingness to invest in storage protection technologies. *Journal of Agriculture and Food Research*, 14, 100691. <https://doi.org/10.1016/j.jafr.2023.100691>
- Martin, D. T., Baributsa, D., Huesing, J. E., Williams, S. B., & Murdock, L. L. (2015). PICS bags protect wheat grain, *Triticum aestivum* (L.), against rice weevil, *Sitophilus oryzae* (L.)(Coleoptera: Curculionidae). *Journal of Stored Products Research*, 63, 22-30. <https://doi.org/10.1016/j.jspr.2015.05.001>

- Misselhorn, A., Aggarwal, P., Ericksen, P., Gregory, P., Horn-Phathanothai, L., Ingram, J., & Wiebe, K. (2012). A vision for attaining food security. *Current opinion in environmental sustainability*, 4(1), 7-17. <https://doi.org/10.1016/j.cosust.2012.01.008>
- Mobolade, A. J., Bunindro, N., Sahoo, D., & Rajashekar, Y. (2019). Traditional methods of food grains preservation and storage in Nigeria and India. *Annals of Agricultural Sciences*, 64(2), 196-205. <https://doi.org/10.1016/j.aosas.2019.12.003>
- Mohapatra, D., Kumar, S., Kotwaliwale, N., & Singh, K. K. (2017). Critical factors responsible for fungi growth in stored food grains and non-Chemical approaches for their control. *Industrial Crops and Products*, 108, 162-182. <https://doi.org/10.1016/j.indcrop.2017.06.039>
- Mompremier, R., Bern, C., Bowers, E., Brumm, T., & Maier, D. (2022). Field testing of Purdue improved crop storage (PICS) bag maize storage in Haiti. *Journal of Stored Products and Postharvest Research*, 13(1), 1-5. <https://doi.org/10.5897/JSPPR2021.0323>
- Murdock, L. L., Margam, V., Baoua, I., Balfe, S., & Shade, R. E. (2012). Death by desiccation: effects of hermetic storage on cowpea bruchids. *Journal of stored products research*, 49, 166-170. <https://doi.org/10.1016/j.jspr.2012.01.002>
- Nag, M. K. (2024). Development and inner environment analysis of advance and eco-friendly cementitious silo for postharvest grain protection and shelf life extension for medium and small-scale farmers. *Journal of Stored Products Research*, 106, 102290. <https://doi.org/10.1016/j.jspr.2024.102290>
- Ng'ang'a, J. K. (2016). Effects of Hermetic Bag Storage on Insect Pest Damage, Mould Infection and a Flatoxin Contamination on Maize Grain in Makueni County, Kenya (*Doctoral dissertation, Jomo Kenyatta university of Agriculture and Technology*).
- Nouhoheflin, T., Coulibaly, J. Y., D'Alessandro, S., Aitchédji, C. C., Damisa, M., Baributsa, D., & Lowenberg-DeBoer, J. (2017). Management lessons learned in supply chain development: the experience of PICS bags in West and Central Africa. *International Food and Agribusiness Management Review*, 20(3), 427-438. <https://doi.org/10.22434/IFAMR2016.0167>
- Lemaire, L. L., & Baoua, I. B. (2014). On Purdue Improved Cowpea Storage (PICS) technology: background, mode of action, future prospects. *Journal of Stored Products Research*, 58, 3-11. <https://doi.org/10.1016/j.jspr.2014.02.006>
- Muriuki, N., Munyua, C., & Wanga, D. (2016). Communication channels in adoption of technology with a focus on the use of Purdue improved crop storage (PICS) among small scale maize farmers in Kenya. *Journal of Biology, Agriculture and Healthcare*, 6(18), 8-12.
- Mutambuki, K., Affognon, H., Likhayo, P. and Baribusta, D. 2019. Evaluation of purdue improved crop storage triple layer hermetic storage bag against *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) and *Sitophilus zeamais* (Motsch.) (Coleoptera: Curculionidae). *Insects*, 10(7), 204. <https://doi:10.3390/insects10070204>.
- Mutungi, C., Imathiu, S., & Affognon, H. (2016). Effect of triple-layer hermetic bagging on mould infection and aflatoxin contamination of maize during multi-month on-farm storage in Kenya. *Journal of Stored Products Research*, 69, 119-128. <https://doi.org/10.1016/j.jspr.2016.07.005>
- Mutungi, C., Affognon, H. D., Njoroge, A. W., Manono, J., Baributsa, D., & Murdock, L. L. (2015). Triple-layer plastic bags protect dry common beans (*Phaseolus vulgaris*) against damage by *Acanthoscelides obtectus* (Coleoptera: Chrysomelidae) during storage. *Journal of Economic Entomology*, 108(5), 2479-2488. <https://doi.org/10.1093/jee/fov197>
- Mutungi, C. M., Affognon, H. D., Njoroge, A. W., Baributsa, D. & Murdock, L. L. 2014. Storage of mung bean (*Vigna radiata* [L.] Wilczek) and pigeonpea grains (*Cajanus cajan* [L.] Millsp) in hermetic triple-layer bags stops losses caused by *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae). *Journal of Stored Products Research*, 58, 39- 47. <https://doi.org/10.1016/j.jspr.2014.03.004>.

- Mvumi, B. M., & Stathers, T. (2020). Supporting smallholder farmers in developing countries to improve postharvest management of staple grains: the role of loss reduction technologies. In *Advances in postharvest management of cereals and grains* (pp. 389-444). Burleigh Dodds Science Publishing.
- Ndaghu, N. N., Abdoulaye, T., Mustapha, A., Fani, D. C. R., Tabetando, R., Henrietta, U. U., & Kamsang, S. L. (2023). Gender differentiation on the determinants and intensity of adoption of Purdue improved cowpea storage (PICS) bags in Northern Nigeria. *Heliyon*, 9(12).
- Njoroge, A. W., Affognon, H. D., Mutungi, C. M., Manono, J., Lamuka, P. O. & Murdock, L. L. (2014). Triple bag hermetic storage delivers a lethal punch to *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in stored maize. *Journal of Stored Products Research* 58, 12–19. <https://doi.org/10.1016/j.jspr.2014.02.005>.
- Nwaubani, S. I., Otitodun, G. O., Ajao, S. K., Opit, G. P., Ala, A. A., Omobowale, M. O., ... & Ileleji, K. E. (2020). Assessing efficacies of insect pest management methods for stored bagged maize preservation in storehouses located in Nigerian markets. *Journal of Stored Products Research*, 86, 101566. <https://doi.org/10.1016/j.jspr.2019.101566>
- Odjo, S., Alakonya, A. E., Rosales-Nolasco, A., Molina, A. L., Munoz, C., & Palacios-Rojas, N. (2022). Occurrence and postharvest strategies to help mitigate aflatoxins and fumonisins in maize and their co-exposure to consumers in Mexico and Central America. *Food Control*, 138, 108968. <https://doi.org/10.1016/j.foodcont.2022.108968>
- Okori, F., Cherotich, S., Baidhe, E., Komakech, A. J., & Banadda, N. (2022). Grain hermetic storage and post-harvest loss reduction in sub-saharan Africa: Effects on grain damage, weight loss, germination, insect infestation, and mold and mycotoxin contamination. *Journal of Biosystems Engineering*, 47(1), 48-68. <https://doi.org/10.1007/s42853-022-00130-4>
- Okparavero, N. F., Grace, O. O., Rukayat, Q., Jimoh, O. M., Ishola, T. D., Okunlade, A. F., & Akande, E. T. (2024). Effective Storage Structures for Preservation of Stored Grains in Nigeria: A Review. *Ceylon Journal of Science*, 53(1), 139-147. <https://doi.org/10.4038/cjs.v53i1.8194>
- Omodara, M. A., Montross, M. D., McNeill, S. G., & Bessin, R. (2020). Impact of storage environment on the micro-climate and grain moisture in polypropylene storage bags. In *2020 ASABE Annual International Virtual Meeting* (p. 1). American Society of Agricultural and Biological Engineers.
- Omotilewa, O. J., & Baributsa, D. (2022). Assessing the private sector's efforts in improving the supply chain of hermetic bags in East Africa. *Sustainability*, 14(19), 12579. <https://doi.org/10.3390/su141912579>
- Omotilewa, O. J. (2017). *The Adoption and Impacts of Improved Storage Technology Among Smallholder Farm Households in Uganda* (Doctoral dissertation, Purdue University).
- Oyewole, O. S., Raji, M. A., Kazeem, A. A., Ajao, T. O., Ibitoye, O., Abel, O. O., ... & Adewunmi, E. O. (2025). Smart Technological Innovations for Postharvest Loss Reduction: A Review. *FUDMA Journal of Sciences*, 9(6), 299-307. <https://doi.org/10.33003/fjs-2025-0906-3605>
- Purdue University. (2020). PICS3 Project Overview. Available at: <https://www.purdue.edu/pics>
- Saha, N. C., Ghosh, A. K., Garg, M., & Sadhu, S. D. (2022). Flexible Packaging Material—Manufacturing Processes and Its Application. In *Food Packaging: Materials, Techniques and Environmental Issues* (pp. 47-87). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-16-4233-3_2
- Sanon, A., Dabiré-Binso, L. C., & Ba, N. M. (2011). Triple-bagging of cowpeas within high density polyethylene bags to control the cowpea beetle *Callosobruchus maculatus* F.(Coleoptera: Bruchidae). *Journal of stored products research*, 47(3), 210-215. <https://doi.org/10.1016/j.jspr.2011.02.003>

- Sudini, H., Rao, G. R., Gowda, C. L. L., Chandrika, R., Margam, V., Rathore, A., & Murdock, L. L. (2015). Purdue Improved Crop Storage (PICS) bags for safe storage of groundnuts. *Journal of Stored Products Research*, 64, 133-138. <https://doi.org/10.1016/j.jspr.2014.09.002>
- Sugri, I., Abubakari, M., Owusu, R. K., & Bidzakin, J. K. (2021). Postharvest losses and mitigating technologies: evidence from Upper East Region of Ghana. *Sustainable Futures*, 3, 100048. <https://doi.org/10.1016/j.sftr.2021.100048>
- Stathers, T., & Mvumi, B. (2020). Challenges and initiatives in reducing postharvest food losses and food waste: sub-Saharan Africa. In *Preventing food losses and waste to achieve food security and sustainability* (pp. 729-786).
- Vales, M. I., Ranga Rao, G. V., Sudini, H., Patil, S. B. & Murdock, L. L. (2014). Effective and economic storage of pigeonpea seed in triple layer plastic bags. *Journal of Stored Products Research*, 58, 29–38. <https://doi.org/10.1016/j.jspr.2014.01.004>.
- Waongo, A., Traore, F., Ba, M. N., Dabire-Binso, C., Murdock, L. L., Baributsa, D., & Sanon, A. (2019). Effects of PICS bags on insect pests of sorghum during long-term storage in Burkina Faso. *Journal of stored products research*, 83, 261-266. <https://doi.org/10.1016/j.jspr.2019.07.010>
- Williams, S. B., Murdock, L. L., & Baributsa, D. (2017). Sorghum seed storage in Purdue Improved Crop Storage (PICS) bags and improvised containers. *Journal of Stored Products Research*, 72, 138-142. <https://doi.org/10.1016/j.jspr.2017.04.004>
- Ziegler, V., Paraginski, R. T., & Ferreira, C. D. (2021). Grain storage systems and effects of moisture, temperature and time on grain quality-A review. *Journal of Stored Products Research*, 91, 101770. <https://doi.org/10.1016/j.jspr.2021.101770>