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Increasing adoption of grain postharvest technology by smallholder farmers: a five-pronged strategy

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Grain postharvest losses (PHLs) reduce food security, income stability, and climate resilience among smallholder farmers in sub-Saharan Africa and South Asia. Proven technologies, e.g., hermetic storage bags and metal silos, are available, but significant non-technical barriers to adoption remain. These complex barriers include limited awareness and training, limited local availability, initial high costs, low harvest volumes, underestimation of losses, socio-cultural constraints, and weak institutional and policy support. We propose a five-pronged strategy to increase adoption. In particular: (1) Strengthening farmer knowledge and training systems; (2) Localizing the development and distribution of postharvest technologies; (3) Expanding access to affordable and flexible financing; (4) Reinforcing policy and institutional frameworks; and (5) Embedding postharvest practices within climate-smart, market-driven value chains. Implementation of this strategy positions postharvest management as a structural driver of rural transformation by linking grain loss reduction to increased productivity, enhanced market participation, and livelihood resilience.

KEYWORDS

farmer training, grain storage, hermetic technologies, institutional barriers, postharvest extension, postharvest investment, technology dissemination

1 Introduction

Reducing postharvest losses (PHLs) of grain is a pressing priority for strengthening food security, improving rural livelihoods, and building resilience to climate change and variability. Grains such as maize, rice, millet, wheat, and sorghum are essential staples in sub-Saharan Africa and South Asia, yet large volumes of these crops are lost after harvest due to inadequate harvesting, drying, handling, storage, transportation, and marketing systems. In Sub-Saharan Africa alone, postharvest losses for cereals are estimated at 20–30%, translating into over USD 4 billion in annual losses (Kumar and Kalita, 2017; FAO, 2019; Zorya et al., 2011). FAO data further suggest that up to 37% of food produced in the region is lost before it reaches consumers. These losses are sufficient to supply the caloric needs of 48 million people (Zorya et al., 2011). In South Asia, rice and wheat losses are similarly high, estimated at 10–20%, largely due to inefficiencies in postharvest drying and pest control systems (World Bank, 2018). More grain has been abandoned to postharvest losses in sub-Saharan Africa than food aid received from the USA (Affognon et al., 2015). Decades of innovation have been invested in postharvest technologies, including hermetic storage bags, improved cribs, and metal silos, yet uptake of these technologies by smallholder farmers still remains low (Rwebangira et al., 2022; Ngoma et al., 2025). When used as developed, however, these technologies, e.g., hermetic bags in Tanzania (Brander et al., 2021), can reduce seasonal food insecurity.

The availability of a technology alone is not enough to drive widespread uptake. Adoption is mediated by a combination of behavioral, economic, institutional, and infrastructural drivers (Bisheko and Rejikumar, 2023; Jarman et al., 2023). Smallholders often lack appropriate training, have limited access to finance to meet high upfront costs, and contend with poorly developed distribution systems that make the desired technology difficult to obtain, especially in remote and climate-vulnerable areas (Balana et al., 2022; Rutta, 2022). Socio-cultural dynamics and gaps in knowledge and skills can further deter adoption. For example, training often is targeted at men even though women are responsible for the majority of postharvest activities in many developing countries (Affognon et al., 2015; Lelea et al., 2022). Many farmers are skeptical about the effectiveness or value of modern storage technologies, particularly if they have not observed or experienced them firsthand (Stathers et al., 2020). Weak institutional support, including fragmented extension services and low policy prioritization, complicate the problem further by limiting the environment required for sustained adoption (Devkota et al., 2016).

Studies describing individual constraints are available, but few studies offer integrated strategies that address the system-level factors limiting adoption. Our goal is to relate these somewhat disparate studies to one another and develop a coordinated strategy to address this problem that is grounded in empirical evidence. By embedding postharvest management within climate-smart, market-driven grain value chains, farmers' knowledge will increase, technology development and availability will improve, financing should become more available, and institutional frameworks will be strengthened. By aligning postharvest interventions with broader agricultural, climate, and socio-economic issues, adoption is no longer a stand-alone technical fix but instead is a catalyst for inclusive, scalable rural transformation.

2 Methodological approach

This perspective is grounded in a targeted synthesis of empirical literature and practitioner experience to identify strategic pathways for enhancing the adoption of postharvest grain technologies by smallholder farmers. Rather than conducting an exhaustive review, we applied a purposive search strategy to capture high-relevance peer-reviewed studies, implementation reports, and institutional analyses published between 2011 and 2025. Literature was retrieved through structured searches in Scopus, Web of Science, PubMed, and Google Scholar using combinations of keywords such as "postharvest loss," "postharvest technology," "hermetic storage," "technology adoption," "extension systems," and "smallholder agriculture." Complementary grey literature was drawn from institutional repositories of the FAO, World Bank, CGIAR, and USAID Feed the Future, with emphasis on empirically grounded interventions and policy-relevant insights.

Although the primary focus is on Sub-Saharan Africa and South Asia, the analysis also integrates transferable lessons from Latin America, Southeast Asia, and global initiatives. Particular attention was given to systematic reviews, randomized controlled trials, and implementation-focused case studies that offered evidence on the effectiveness, limitations, and contextual drivers of postharvest technology adoption. The resulting five-pronged framework does not present a universal solution, but rather synthesizes recurrent themes and systems-level insights applicable across diverse smallholder contexts. It is intended to inform the design of integrated, scalable, and evidence-based strategies for policymakers, practitioners, and institutions working to address persistent barriers to postharvest management in low- and middle-income countries.

3 Current barriers to adoption of grain postharvest management technologies by smallholder farmers

3.1 Lack of awareness and training

Overstretched extension services, and inadequate training, especially hands-on sessions, deter smallholder adoption of postharvest technologies. Training targeted at men often misses women farmers (Affognon et al., 2015) and increases risks to food security (Lelea et al., 2022). In some regions, over half of farmers are unaware of established options, e.g., hermetic bags (Okori et al., 2022; Heve et al., 2023). Even if they are aware of the technology, many farmers use the technology incorrectly due to insufficient training (Mbesa et al., 2024).

3.2 Limited local availability of technologies

Limited local market availability of postharvest technologies limits technology adoption by rural smallholder farmers. In remote areas, farmers often must travel long distances to obtain products to improve storage and acquiring solutions can be quite costly in terms of money, effort and time (Moussa et al., 2014; Osei-Asibey et al., 2022; Ngoma et al., 2025). Poor roads and small, often widely dispersed, communities limit the profits, if any, that can be made from local distribution of available technologies (Govereh et al., 2019; Omotilewa and Baributsa, 2022).

3.3 High costs and financial constraints

High costs, often for solutions that are too large for a single family, and limited credit access reduce adoption of postharvest technologies. In Kenya, a 1.8-ton metal silo, which could store grain for a single year for a smallholder household, costs about US$230, which is approximately a year's income for a smallholder farmer and is unaffordable without subsidies (Gitonga et al., 2013). In Malawi, farmers were willing to pay only 42% of the market price for hermetic bags suitable for storing a family's harvest (Masters and Alvarez, 2018). Import duties and shipping expenses can further raise technology costs, while tight margins and unclear economic benefits deter investment (Balana et al., 2022). Additionally, strict loan conditions and bureaucratic hurdles can limit or prevent access even to micro-credit loans of only a few dollars (Teye and Quarshie, 2021).

3.4 Low harvests

Low and unreliable yields make it difficult for smallholder farmers to justify investing in postharvest technologies, as there may not be much grain that needs to be stored for a long period of time, e.g., six months to a year. Many smallholder farmers resort to home-based storage also to reduce theft concerns (George, 2011). Immediate financial needs and lack of postharvest credit often oblige smallholder farmers to sell soon after harvest when prices commonly are the lowest of the year (Onumah and Meijerink, 2012). Grain price fluctuations further discourage investment in long-term storage solutions, which are viewed as risky by smallholder farmers.

3.5 Estimation and documentation of postharvest losses

Smallholder farmers often underestimate postharvest losses in both quantity and quality and thus weaken incentives for adopting mitigation technologies (Baributsa et al., 2021; Ricker-Gilbert et al., 2022). Government efforts to promote adoption also are constrained by poor and limited data. Without reliable knowledge of the size of the problem by farmers or government officials, effective policy and resource allocations cannot be made (Stathers et al., 2020). Unreliable underestimates of losses keep investment in postharvest solutions a low priority. Currently, online postharvest loss estimation systems exist, e.g., www.aphil.net, but are not widely used by policy-makers in decision making.

3.6 Social and cultural barriers

Individual farmers often manage their household grain storage as a family secret, which makes assessment of losses difficult. Often, losses are detected only when grain is taken to a mill to be ground and the quantity and quality of a family's grain can no longer be hidden. Fear of failure and doubts about effectiveness discourage many farmers from adopting new technologies and lead them to cling to traditional practices. Many smallholder farmers are unwilling to change their practices unless they have witnessed that the new practices work well for their neighbors, sometimes for multiple years. Social norms, awareness levels, and traditional practices strongly shape these attitudes (John et al., 2023). Adoption also is influenced by factors such as household size, landholding, storage needs, income, infrastructure, and grain safety concerns (Gitonga et al., 2013; Priya and Mitra, 2020). Some farmers mistakenly believe that improved storage or drying methods may reduce grain quality, which reinforces individual family reluctance and can slow adoption by an entire village (Ngoma et al., 2025).

4 Proposed strategy for enhancing postharvest technology adoption

Addressing postharvest losses by smallholder farmers requires a systems-level approach that goes beyond isolated interventions. We developed a five-pronged framework based on empirical evidence and implementation insights (Table 1). This strategy focuses on interconnected pillars to create an environment in which smallholder farmers have both the tools and the support necessary to adopt and sustain the use of new technologies. The strategy is guided by principles of inclusivity, resilience, and scalability, reflecting the spatial, economic, and gendered realities of smallholder agriculture.

5 Discussion

This article presents a Perspective grounded in empirical evidence and implementation experience, aiming to synthesize a systems-level strategy for improving the adoption of postharvest technologies by smallholder farmers. Reducing PHLs among smallholder farmers requires a coordinated, systemic approach that addresses the interconnected components of farmer knowledge systems, technology access, financing, institutional support, and market integration. Tackling these areas in isolation leads to fragmented efforts and limited sustainability. For instance, expanding access to credit without ensuring technology availability or farmer training is unlikely to yield meaningful adoption. Similarly, deploying technologies in areas lacking reliable extension services or functional markets would constrain their impact. The integrated strategy outlined in Table 1 emphasizes the importance of integrating these components into a single strategy. Implementation must be both multi-dimensional and collaborative. The Ministry of Agriculture should serve as the lead agency, coordinating with research institutions, local governments, private sector actors, and development partners to ensure investment priorities, cohesion and scalability.

The first step in any strategy is to secure the farmer knowledge and training systems. Digital tools offer efficiency and scale, but relying solely on them risks excluding populations with low digital literacy or poor connectivity. Participatory approaches, including Farmer Field Schools, community radio, and peer-led training, provide accessible and trusted learning channels that include women and youth and are better suited to local contexts. Completing this step requires investment in, and deployment of, decentralized, inclusive, and adaptive extension models that link timely information with practical skills development (Dzanku et al., 2022; Ikendi et al., 2024; Jones et al., 2023; Stathers et al., 2013). In Tanzania, the Post Harvest Loss Feed the Future Innovation Lab demonstrated that training combined with hermetic bag distribution reduced seasonal food insecurity by over 25% amongst participating households (Brander et al., 2021).

Effective technologies must be available locally if they are to have impact. Imported storage solutions, while effective, often are too expensive or not widely available, especially in remote areas. Supporting local country-level manufacturing at scale including the initial use of foreign manufacturing where appropriate can reduce costs, improve availability, and enable faster access. The goal should be to eventually establish scalable domestic production capacity that ensures affordability and quality. For example, the large-scale manufacturing of low-cost technologies in China has enabled affordable distribution to

TABLE 1 Potential components of proposed strategies for enhancing the adoption of grain postharvest management technologies by smallholder farmers.

What	Why	How
1. Strengthen Farmer Knowledge & Training Systems	Awareness gaps, improper technology use, and overstretched extension systems limit adoption. Climate change and variability increase spoilage and pest risks, intensifying the need for timely, context-aware knowledge systems (Stathers et al., 2013; Okori et al., 2022; Mbesa et al., 2024).	• Strengthen cooperatives and producer groups to enhance peer learning and improve market access (Othman et al., 2020). • Expand mobile-based extension tools for real-time, climate-responsive guidance (Quandt et al., 2020). • Establish decentralized postharvest demonstration centers to enable hands-on experiential learning. • Integrate postharvest practices into Farmer Field Schools to support continuous learning (Ikendi et al., 2024). • Use community radio and participatory video to build trust and increase awareness of novel postharvest technologies (Dzanku et al., 2022). • Deliver seasonal climate-smart advisories on harvest timing, drying, threshing, storage and marketing through mobile alerts and group sessions (Jones et al., 2023).
2. Localize Technology Supply and Distribution	Limited access, high costs, and climate-sensitive infrastructure constrain uptake. Imported solutions are unaffordable. Poor road networks and dispersed customers limit distribution business viability (Ngoma et al., 2025; Govereh et al., 2019).	• Promote local manufacturing to reduce costs and improve availability (Khder et al., 2020). • Support research into adaptation of appropriate technologies to suit local conditions and promote their use across the entire value chain. • Strengthen rural supply chains with incentives for last-mile distributors. • Enforce quality standards and certification to ensure farmer trust (Mekonen and Wubetie, 2021). • Ensure availability of spare parts and repair services to build long-term reliability (Kundu and Ramdas, 2022). • Develop and promote climate-resilient storage technologies that mitigate floods and excessive heat (Mpala and Simatele, 2024).
3. Expand Affordable Financing Mechanisms	High costs and limited credit restrict technology adoption. Many farmers are only willing to pay a fraction of market prices without financial support (Masters and Alvarez, 2018; Gitonga et al., 2013). Bureaucratic hurdles can block credit access (Teye and Quarshie, 2021).	• Develop seasonal and flexible credit schemes tailored to fit into crop harvest cycles (Bisheko and Rejikumar, 2023). • Implement subsidies and voucher programs to offset technology adoption risks (Omotilewa et al., 2019; Nepali and Maharjan, 2025). • Advocate and support the removal of duty on postharvest equipment and technologies to increase affordability and enhance adoption by smallholder farmers. • Facilitate group-based bulk purchasing to reduce per-unit costs (Dillon et al., 2021). • Integrate financial and advisory support with after-sales service for sustainability (Dupas, 2014; Bensch and Peters, 2020).
4. Strengthen Policy and Institutional Support	Weak institutional mandates and limited integration of postharvest management issues into broader agri-food and climate adaptation strategies impede resource allocation and political prioritization (Muroyiwa et al., 2020; Devkota et al., 2016).	• Integrate postharvest loss reduction into mainstream national agricultural and food security policies. • Policy measures should create a suitable environment for research on postharvest issues. • Improve data collection systems to identify postharvest losses and guide investments (Umbach et al., 2018). • Train local government agencies to implement context-specific postharvest strategies (Sala et al., 2016). • Incorporate postharvest goals into nutrition, trade, and climate adaptation agendas to strengthen multi-sectoral interactions. • Add quality assessment capabilities to existing institutions and make services available affordable.
5. Embed Postharvest Practices in Market Systems	Poor price incentives and weak market linkages reduce motivation to invest in drying, storage or processing improvements. Buyers rarely reward quality preservation (Schwab and Yu, 2024).	• Link storage technologies to premium markets through contracts and certifications (Park et al., 2025). • Promote structured value chains and their modification to stabilize prices and ensure predictable market access for farmers (Schwab and Yu, 2024). • Provide real-time price and quality information to enable informed transactions (Aggarwal et al., 2018). • Offer tax incentives and promote Public-Private Partnerships to catalyze private investment in postharvest services and infrastructure (Suwanda, 2023).

African markets, demonstrating the benefits of manufacturing at scale. Equally critical is investment in last-mile delivery systems. In many African countries, poor road networks and underdeveloped logistics infrastructure severely hinder timely access to technologies. Without strengthening supply chain logistics and distributor networks, even affordable and well-designed products may not reach the farmers when and where they are most needed. The PICS initiative in West Africa fostered local manufacturing of storage bags, reducing prices by 15–30% and expanding last-mile availability (Moussa et al., 2014). Sustainability also requires oversight and technical training to ensure quality products that meet regulatory standards are produced. Such standards, require adequate testing infrastructure, and technical capacity at the local level to meet the market's demands (Ngoma et al., 2025; Kundu and Ramdas, 2022; Mekonen and Wubetie, 2021).

Acceptable products and adequate training mean that financing must be available that enables farmers to purchase and benefit from the improved technology. Subsidies and credit schemes can lower entry barriers, but their effectiveness is maximized when they are embedded within broader support systems. Ideally, flexible credit programs will be tailored to harvest cycles, group-based purchasing arrangements, and targeted voucher programs. Evidence of adequate training should be a requirement for eligibility to participate in a financing program. Bundled financial and technical services focused on capacity building are most likely to support sustained adoption.

Donor programs are important for initial efforts, but a successful strategy will develop a sustainable long-term source of public and private funds (Masters and Alvarez, 2018; Bensch and Peters, 2020; Houmy et al., 2024). Structural limitations persist across regions. Financial constraints are frequently cited, but few subsidy or microcredit schemes are integrated with follow-up training or mechanisms to ensure correct technology use, which undermines their long-term impact (Dupas, 2014). Programs also tend to promote standardized solutions, often ignoring agroecological diversity and local knowledge. This disconnect can reduce the relevance and effectiveness of technologies in specific settings. When properly designed, as in Uganda, subsidy vouchers can result in a 40% increase in hermetic bag use, especially among first-time users (Omotilewa et al., 2019). In parallel, supply chain fragmentation, especially in remote and underserved areas, continues to constrain access. These limitations disproportionately affect women and marginalized groups, who are often excluded from formal distribution channels.

With trained farmers capable of managing improved PHL technology, PHL must now become an essential part of an agricultural policy framework. A nation's entire grain supply is subject to PHL and reducing PHL is as effective as increasing production and usually requires fewer resources. Integrating PHL targets into national agriculture strategies helps align these strategies with on the ground realities, provides incentives for farmer training, technology development, and establishing financial programs that use stored grain as collateral. Concomitant with these changes, Monitoring and Evaluation systems must be developed that capture real-time data on uptake, correct usage, and impacts across diverse contexts, including behavioral change, economic benefits, food safety, and resilience to generate the evidence needed to inform policy and attract investment. These feedback loops enable the scaling of postharvest innovations to be driven by evidence rather than by anecdote. The current lack of clear mandates, means that this critical portion of agricultural policy has limited visibility with piece meal, externally driven, unsustainable implementation. Dedicated budget lines for and better monitoring of postharvest performance will increase accountability and enable measurement of long-term impact (Muroyiwa et al., 2020; Totobesola et al., 2022; Umbach et al., 2018).

Market integration is the final, and perhaps most decisive, pillar in determining long-term sustainability. Investing in improved storage and handling practices requires a clear economic incentive. PHL is critical for both grain quality and quantity, especially in humid tropical regions of sub-Saharan Africa and Southeast Asia, where high temperatures and humidity accelerate spoilage through mold growth and insect damage. In these settings, quantity losses can be substantial. Improved PHL technology must be linked to premium markets and certification schemes that enable farmers to be rewarded with higher prices for reducing postharvest losses. Institutional and international buyers must be willing to pay for quality. If they do not, then improved technologies will remain underutilized despite the increases in food safety and nutrition that they provide (Schwab and Yu, 2024; Park et al., 2025; Aggarwal et al., 2018; Urugo et al., 2024). Making PHL a priority may require rethinking agricultural investment priorities, as some of the resources currently allocated to input subsidies, e.g., fertilizer, may need to be reallocated to strengthen PHL activities and technologies. Such reallocation would increase the return on production by reducing systemic food system losses.

Private sector involvement, particularly from multinational corporations, has been minimal, which has hindered the widespread scaling of PHL technologies. Most advances have stemmed from university-driven innovations scaled by resource-constrained start-ups. There is a major opportunity to develop innovative business models that bundle PHL technologies with widely adopted consumer goods, such as mobile phones. Multinational telecom companies already possess extensive distribution networks, large marketing budgets, and logistics infrastructure that could be leveraged to reach remote farming communities efficiently.

In conclusion, PHL reduction must become a central component of agricultural transformation rather than a secondary concern. We have proposed an integrated strategy that addresses these challenges holistically. Implementation of this strategy must be deliberate, context-sensitive, and sustained by long-term commitments at national and local levels. While success depends on continually improving technology and farmer training, long-term success requires societal changes in finance, policy and differential product acceptability. Collectively these changes can increase the overall benefits from agricultural investments. Ultimately, the ability to preserve what is already produced will determine the resilience, equity, and sustainability of tomorrow's food systems. Future research and programming should prioritize longitudinal studies that track behavioral and economic outcomes over time, particularly across gender, climate vulnerability, and agroecological zones. Without these data to design and evaluate programs, interventions risk reinforcing existing inequalities and failing to scale effectively.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: No data is involved in this perspective article.

Author contributions

TN-N: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing, Investigation. JL: Conceptualization, Writing – original draft, Writing – review & editing, Funding acquisition. MM: Writing – original draft, Writing – review & editing. BMM: Writing – original draft, Writing – review & editing. TC: Writing – original draft, Writing – review & editing. EK: Writing – original draft, Writing – review & editing. AT: Writing – original draft, Writing – review & editing. BK: Writing – original draft, Writing – review & editing. AG: Writing – original draft, Writing – review & editing. BM: Writing – original draft, Writing – review & editing. JH: Writing – original draft, Writing – review & editing, Funding acquisition. LM: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Supervision.

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References

Affognon, H., Mutungi, C., Sanginga, P., and Borgemeister, C. (2015). Unpacking postharvest losses in sub-Saharan Africa: a meta-analysis. *World Dev.* 66, 49–68. doi: 10.1016/j.worlddev.2014.08.002

Aggarwal, S., Francis, E., and Robinson, J. (2018). Grain today, gain tomorrow: evidence from a storage experiment with savings clubs in Kenya. *J. Dev. Econ.* 134, 1–15. doi: 10.1016/j.jdeveco.2018.04.001

Balana, B. B., Aghadi, C. N., and Ogunniyi, A. I. (2022). Improving livelihoods through postharvest loss management: evidence from Nigeria. *Food Secur.* 14, 249–265. doi: 10.1007/s12571-021-01196-2

Baributsa, D., Díaz-Valderrama, J., Mughanda, D., Lubanzadio, A., Nshombo, J., Sperling, L., et al. (2021). Grain handling and storage in Lubero and Rutshuru territories in the north Kivu province, the Democratic Republic of Congo. *Sustainability* 13:9580. doi: 10.3390/SU13179580

Bensch, G., and Peters, J. (2020). One-off subsidies and long-run adoption—experimental evidence on improved cooking stoves in Senegal. *Am. J. Agric. Econ.* 102, 72–90. doi: 10.1093/ajae/aaz023

Bisheko, M. J., and Rejikumar, G. (2023). Major barriers to adoption of improved postharvest technologies among smallholder farmers in sub-Saharan Africa and South Asia: a systematic literature review. *World Dev. Sustain.* 2:100070. doi: 10.1016/j.wds.2023.100070

Brander, M., Bernauer, T., and Huss, M. (2021). Improved on-farm storage reduces seasonal food insecurity of smallholder farmer households – evidence from a randomized control trial in Tanzania. *Food Policy* 98:101891. doi: 10.1016/j.foodpol.2020.101891

Devkota, K., Thapa, D., and Dhungana, H. (2016). Weak institutional interaction: reason for poor agricultural extension services delivery in Nepal. *New Angle Nepal J. Soc. Sci. Public Policy* 4, 88–103. doi: 10.53037/na.v4i1.22

Dillon, B., De Weerdt, J., and O'Donoghue, T. (2021). Paying more for less: why don't households in Tanzania take advantage of bulk discounts? *World Bank Econ. Rev.* 35, 148–179. doi: 10.1093/wber/lhz020

Dupas, P. (2014). Short-run subsidies and long-run adoption of new health products: evidence from a field experiment. *Econometrica* 82, 197–228. doi: 10.3982/ECTA9508

Dzanku, F. M., Osei, R. D., Nkegbe, P. K., and Osei-Akoto, I. (2022). Information delivery channels and agricultural technology uptake: experimental evidence from Ghana. *Eur. Rev. Agric. Econ.* 49, 82–120. doi: 10.1093/erae/jbaa032

FAO (2019). The State of Food and Agriculture 2019: Moving forward on food loss and waste reduction. Italy: Food and Agriculture Organization of the United Nations (FAO).

George, M. L. C. (2011). Effective grain storage for better livelihoods of African farmers project: Completion report June 2008 to February 2011. Available online at: https://repository.cimmyt.org/server/api/core/bitstreams/5eb5f88d-afa3-424c-935b-1736f2819717/content (Accessed July 22, 2025).

Gitonga, Z. M., De Groote, H., Kassie, M., and Tefera, T. (2013). Impact of metal silos on households' maize storage, storage losses and food security: an application of a propensity score matching. *Food Policy* 43, 44–55. doi: 10.1016/j.foodpol.2013.08.005

Govereh, J., Muchetu, R. G., Mvumi, B. M., and Chuma, T. (2019). Analysis of distribution systems for supply of synthetic grain protectants to maize smallholder farmers in Zimbabwe: implications for hermetic grain storage bag distribution. *J. Stored Prod. Res.* 84:101520. doi: 10.1016/j.jspr.2019.101520

Heve, W. K., Ninsin, K. D., Osei-Owusu, J., Aidoo, O. F., Akolaa, R. A., and Larbi, L. (2023). Smallholder farmers' knowledge, practices and perceptions associated with grain storage and hermetic technology in southern Ghana: implications for awareness and training. *Inf. Dev.* 41:02666669231171930. doi: 10.1177/02666669231171930

Houmy, K., Mpagalile, J., Flores Rojas, M., and Odjo, S. (2024). "The way forward: recommendations for further actions" in Post-harvest management: Bridging gaps and embracing innovations. eds. M. F. Rojas, K. Houmy and O. Fawole (Rome: FAO).

Ikendi, S., Owusu, F., Oberhauser, A., Masinde, D., and Bain, C. (2024). Assessment of agronomy extension education programs on empowerment of farmers in food production in rural Uganda. *J. Agric. Educ.* 65, 99–125. doi: 10.5032/jae.v65i1.98

Jarman, A., Thompson, J., McGuire, E., Reid, M., Rubsam, S., Becker, K., et al. (2023). Postharvest technologies for small-scale farmers in low-and middle-income countries: a call to action. *Postharvest Biol. Technol.* 206:112491. doi: 10.1016/j.postharvbio.2023.112491

John, D., Hussin, N., Shahibi, M. S., Ahmad, M., Hashim, H., and Ametefe, D. S. (2023). A systematic review on the factors governing precision agriculture adoption among small-scale farmers. *Outlook Agric.* 52, 469–485. doi: 10.1177/00307270231205640

Jones, E. O., Tham-Agyekum, E. K., Ankuyi, F., Ankrah, D. A., Akaba, S., Shafiwu, A. B., et al. (2023). Mobile agricultural extension delivery and climate-smart agricultural practices in a time of a pandemic: evidence from southern Ghana. *Environ. Sustain. Indic.* 19:100274. doi: 10.1016/j.indic.2023.100274

Khder, S. I., Alwakeel, A., SaifAldawla, A., Ali, A. A., Kadoma, M., Hassan, N., et al. (2020). Measuring availability and prices of locally produced and imported medicines in Sudan. *JMID* 1, 1–14. doi: 10.14302/issn.2641-5526.jmid-19-3119

Kumar, D., and Kalita, P. (2017). Reducing postharvest losses during storage of grain crops to strengthen food security in developing countries. *Foods* 6:8. doi: 10.3390/foods6010008

Kundu, A., and Ramdas, K. (2022). Timely after-sales service and technology adoption: evidence from the off-grid solar market in Uganda. *Manuf. Serv. Oper. Manag.* 24, 1329–1348. doi: 10.1287/msom.2021.1060

Lelea, M., Garbaba, C., Guluma, A., and Hensel, O. (2022). Gendering post-harvest loss research: responsibilities of women and men to manage maize after harvest in Southwest Ethiopia. *Food Secur.* 14, 951–963. doi: 10.1007/s12571-022-01259-y

Masters, W. A., and Alvarez, G. G. (2018). Willingness to pay for hermetic grain storage bags in Malawi. Available online at: https://ideas.repec.org/p/ags/iaae18/277295.html (Accessed July 22, 2025)

Mbesa, B., Makindara, J., Kadigi, M., Majubwa, R., and Madege, R. (2024). Effect of training on knowledge, attitude, and practice on the use of hermetic storage technologies among smallholder farmers in Tanzania. *Afr. J. Empir. Res.* 5, 881–893. doi: 10.51867/ajernet.5.2.79

Mekonen, T. K., and Wubetie, B. Y. (2021). Determinants of the use of hermetic storage bags for maize storage among smallholder farmers in Northwest Ethiopia. *Adv. Agric.* 2021, 1–11. doi: 10.1155/2021/6644039

Moussa, B., Abdoulaye, T., Coulibaly, O., Baributsa, D., and Lowenberg-DeBoer, J. (2014). Adoption of on-farm hermetic storage for cowpea in west and Central Africa in 2012. *J. Stored Prod. Res.* 58, 77–86. doi: 10.1016/j.jspr.2014.02.008

Mpala, T. A., and Simatele, M. D. (2024). Climate-smart agricultural practices among rural farmers in Masvingo district of Zimbabwe: perspectives on the mitigation strategies to drought and water scarcity for improved crop production. *Front. Sustain. Food Syst.* 7:1298908. doi: 10.3389/fsufs.2023.1298908

Muroyiwa, B., Shokopa, L., Likoetla, P., and Rantlo, M. (2020). Integration of post-harvest management in agricultural policy and strategies to minimize post harvest losses in Lesotho. *J. Dev. Agric. Econ.* 12, 84–94. doi: 10.5897/JDAE2019.1082

Nepali, D. K., and Maharjan, K. L. (2025). Assessing the impact of hermetic storage technology on storage quantity and post-harvest storage losses among smallholding maize farmers in Nepal. *Agriculture* 15:151. doi: 10.3390/agriculture15020151

Ngoma, T. N., Leslie, J. F., Katengeza, S. P., Gama, A. P., Mvumi, B. M., Chamboko, T., et al. (2025). Barriers to hermetic bag adoption among smallholder farmers in Malawi. *Sustainability* 17, 1–10. doi: 10.3390/su17031231

Okori, F., Cherotich, S., Abaca, A., Baidhe, E., Adibaku, F., and Onyinge, J. (2022). Grain hermetic storage adoption in northern Uganda: awareness, use, and the constraints to technology adoption. *Agric. Sci.* 13, 989–1011. doi: 10.4236/as.2022.139061

Omotilewa, O. J., Ricker-Gilbert, J., and Ainembabazi, J. H. (2019). Subsidies for agricultural technology adoption: evidence from a randomized experiment with improved grain storage bags in Uganda. *Am. J. Agric. Econ.* 101, 753–772. doi: 10.1093/ajae/aay108

Omotilewa, O. J., and Baributsa, D. (2022). Assessing the private sector's efforts in improving the supply chain of hermetic bags in East Africa. *Sustainability* 14:12579. doi: 10.3390/su141912579

Onumah, G., and Meijerink, G. W. (2012). Innovative agricultural financing models. Hauge, Norway: Agrinatura.

Osei-Asibey, R. K., Wireko-Manu, F. D., Aidoo, R., Boakye-Achampong, S., Mills-Robertson, F. C., and Baributsa, D. (2022). Farmers' perception of the use and benefits of cowpea storage methods in northern Ghana. *Sustainability* 14:5129. doi: 10.3390/su14095129

Othman, M. S., Oughton, E., and Garrod, G. (2020). Significance of farming groups for resource access and livelihood improvement of rural smallholder women farmers. *Dev. Pract.* 30, 586–598. doi: 10.1080/09614524.2020.1764502

Park, S., Yuan, Z., and Zhang, H. (2025). Technology training, buyer-supplier relationship, and quality upgrading in an agricultural supply chain. *Rev. Econ. Stat.* 107, 711–727. doi: 10.1162/rest_a_01341

Priya, P., and Mitra, S. (2020). Post-production decisions in agriculture: understanding postharvest storage and marketing decisions of smallholder farmers. *Food Secur.* 12, 1317–1329. doi: 10.1007/s12571-020-01044-9

Quandt, A., Salerno, J. D., Neff, J. C., Baird, T. D., Herrick, J. E., McCabe, J. T., et al. (2020). Mobile phone use is associated with higher smallholder agricultural productivity in Tanzania, East Africa. *PLoS One* 15:e0237337. doi: 10.1371/journal.pone.0237337

Ricker-Gilbert, J., Omotilewa, O., and Kadjo, D. (2022). The economics of postharvest loss and loss-preventing technologies in developing countries. *Annu. Rev. Resour. Econ.* 14, 243–265. doi: 10.1146/annurev-resource-111820-020601

Rutta, E. W. (2022). Understanding barriers impeding the deployment of solar-powered cold storage technologies for post-harvest tomato losses reduction: insights from small-scale farmers in Tanzania. *Front. Sustain. Food Syst.* 6:990528. doi: 10.3389/fsufs.2022.990528

Rwebangira, E. V., Silayo, V. C., and Mrema, G. C. (2022). Factors that influence smallholder farmers' decisions to employ hermetic bag technology for maize grain storage in Kilosa District, Tanzania. *Int. J. Sci. Res. Updates* 4, 346–355. doi: 10.53430/ijsru.2022.4.1.0141

Sala, S., Rossi, F., and David, S. (2016). Supporting agricultural extension towards climate-smart agriculture: an overview of existing tools. Global Alliance for Climate Smart Agriculture (GASCA)/FAO, Italy, CABI abstracts, pp. 88, ref. 9.

Schwab, B., and Yu, J. (2024). Guaranteed storage? Risk and credit constraints in the demand for postharvest technology. *Oxf. Econ. Pap.* 77:gpae027. doi: 10.1093/oep/gpae027

Stathers, T., Lamboll, R., and Mvumi, B. M. (2013). Postharvest agriculture in changing climates: its importance to African smallholder farmers. *Food Secur.* 5, 361–392. doi: 10.1007/s12571-013-0262-z

Stathers, T., Holcroft, D., Kitinoja, L., Mvumi, B. M., English, A., Omotilewa, O., et al. (2020). A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asia. *Nat. Sustain.* 3, 821–835. doi: 10.1038/s41893-020-00622-1

Suwanda, S. (2023). The role of tax incentives in encouraging innovation and technology adoption in industrial management. *Atestasi J. Ilm. Akunt.* 6, 718–729. doi: 10.57178/atestasi.v6i2.737

Teye, E. S., and Quarshie, P. T. (2021). Impact of agriculture finance in modern technologies adoption for enhanced productivity and rural household economic well being in Ghana: a case study of rice farmers in Shai-Osudoku District. *S. Afr. Geogr. J.* 104, 231–250. doi: 10.1080/03736245.2021.1962395

Totobesola, M., Delve, R., Nkundimana, J. D. A., Cini, L., Gianfelici, F., Mvumi, B., et al. (2022). A holistic approach to food loss reduction in Africa: food loss analysis, integrated capacity development and policy implications. *Food Secur.* 14, 1401–1415. doi: 10.1007/s12571-021-01243-y

Umbach, G., Guidi, C. F., and Russo, M. (2018). Evidence-based policy making: From data to decision-making. Policy Brief, European University Institute, 2018/15. Available online at: https://www.eui.eu/past-courses?id=evidence-based-policy-making-from-data-to-decision-making (Accessed July 22, 2025)

Urugo, M. M., Yohannis, E., Teka, T. A., Gemede, H. F., Tola, Y. B., Forsido, S. F., et al. (2024). Addressing post-harvest losses through agro-processing for sustainable development in Ethiopia. *J. Agric. Food Res.* 18:101316. doi: 10.1016/j.jafr.2024.101316

World Bank (2018). "Agriculture in Africa: telling myths from facts" in Directions in development—Agriculture and rural development. eds. L. Christiaensen and L. Demery (Washington, DC: World Bank).

Zorya, S., Morgan, N., Diaz Rios, L., Hodges, R., Bennett, B., Stathers, T., et al. (2011). Missing Food: The Case of Postharvest Grain Losses in sub-Saharan Africa. Technical Report. Washington, DC, USA: The International Bank for Reconstruction and Development / The World Bank.