SUMMARY REPORT: SCALING ADOPTION OF HERMETIC POST-HARVEST STORAGE TECHNOLOGIES IN UGANDA

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The Comprehensive Initiative on Technology Evaluation (CITE) at MIT is a program dedicated to developing methods for product evaluation in global development. CITE is led by an interdisciplinary team, and draws upon diverse expertise to evaluate products and develop an understanding of what makes products successful in emerging markets.

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Table of Contents

Introduction

Post-harvest losses, due to pests (e.g., insects, rodents, birds) or mycotoxins produced by mold, are an enduring problem throughout the developing world. It is estimated that 54% of food losses occur during production, post-harvest handling, and storage. This post-harvest loss (PHL) is responsible for economic costs estimated at US $750 billion.[1 2]

Various storage technologies have been developed to reduce post-harvest loss, including silos, canisters/drums, woven bags, plastic bags, insect-regulated bags, refrigerated containers, and adaptations to traditional technologies. Many of these products have been piloted in small-scale programs to improve the lives of smallholder farmers in Africa, Southeast Asia, and Central America. However, these technologies have not scaled up to reach broad market penetration.

In 2015, researchers in the MIT Comprehensive Initiative on Technology Evaluation (CITE) conducted a study to better understand the scalability of improved post-harvest storage technologies. The study focused on the World Food Program (WFP) Special Operation 200617 (SO1) in Uganda, which aimed to address post-harvest losses through improved post-harvest handling and the introduction of hermetic crop storage technologies. Operations included training farmers on improved post-harvest processing techniques and establishing supply chains of storage technologies to sell at subsidized prices, which enabled farmers to practice the techniques. The CITE study complements WFP efforts to learn and adapt by gathering and analyzing additional data from supply chain actors and farmers.

This document summarizes the study design, results, findings, and recommendations, which are detailed further in a comprehensive report of the same name. Following a brief introduction to the study context and approach, the results for each technology are organized in sections: the **impact** on farmer's well-being; the farmer's **willingness to pay** for equipment; the **supply chain capability** to make affordable equipment available; and projected **scalability** of adoption. It concludes with findings and recommendations to scale post-harvest storage technologies and to apply the research approaches more generally.

[1] FAO. (2013). Food wastage footprint - Impacts on natural resources (p. 63).
[2] FAO. (2011). Global Food Losses and Food Waste Report.

Context

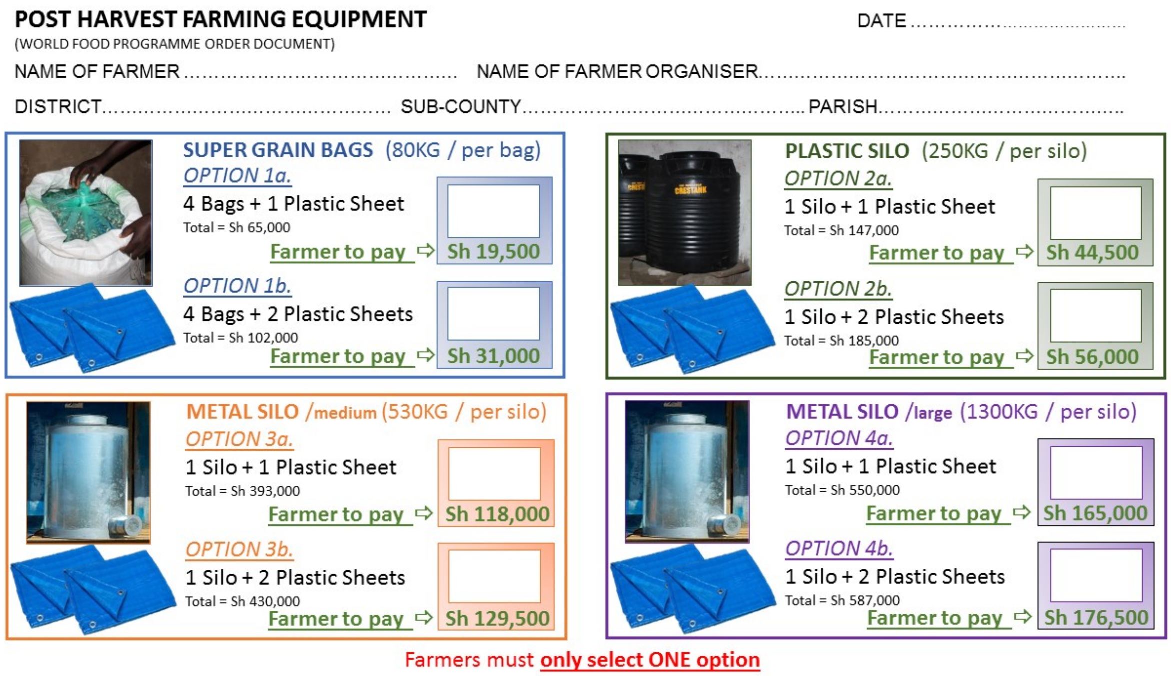
Agriculture lies at the heart of Uganda's economic and social existence: 84% of citizens, 31.8 million people, live in rural areas, and agriculture accounts for 66% of national employment.[3] Smallholder farmers who work on less than two hectares of land account for 80% of agricultural workers and account for 70% of national agricultural production. The planting, harvesting, storing and selling of crops are essential for smallholder farmers' well-being, and for the country's socio-economic development. Issues with the storage phase are receiving more focus, in part due to evidence such as the post-harvest weight loss for maize in Uganda from 2004-2012 ranged from 17-26%.[4] In addition, the mycotoxins that are produced by some molds are less noticeable and can have serious acute and chronic effects on human health, such as the induction of hepatocellular carcinoma or sudden death due to acute toxicity in the case of aflatoxins.[5] Increasing awareness of these harmful effects of mycotoxins on the health and productivity of human and animals have persuaded many countries to implement regulations for maximum tolerable levels of these compounds in human food and animal feed.[6]

The WFP Special Operation 200617 (SO1) in Uganda was part of a four-year project with two objectives: (1) to reduce post-harvest crop loss in Uganda by training farmers on improved post-harvest handling techniques, paired with the introduction of subsidized, hermetic crop storage technologies; and (2) to serve as a catalyst for the private sector to develop business models for post-harvest loss reduction that are market driven and self-sustaining. Hermetic storage technologies were chosen because, when properly sealed, CO2 replaces oxygen through respiration of both the commodity and insects. The lack of oxygen kills the insects and halts the growth of molds that are naturally present in harvested grains.

The SO1 project sought to train 16,600 farmers in 28 districts and sell equipment with a 70% subsidy. At trainings, farmers were offered the choice to purchase one of four technologies: hermetic crop bags, plastic silo, medium metal silo, and large metal silo. These products were paired with plastic tarpaulins (tarps) for drying crops. The equipment order sheet is shown in Figure 1. Before SO1, the hermetic crop storage sector in Uganda was limited to imported crop bags. WFP worked with a local water tank manufacturer to design the plastic silo and with

[3] World Bank, Data Bank, Global Development Indicators.
[4] African Postharvest Losses Information System, http://www.aphlis.net/index.php?form=losses_estimates&co_id=50&c_id=324, accessed September 24, 2016.
[5] Warth, B., et. al., 2012. Quantitation of mycotoxins in food and feed from Burkina Faso and Mozambique using a modern LC-MS/MS multitoxin method. *Journal of agricultural and food chemistry*, 60(36).
[6] Suleiman, R.A. and Rosentrater, K.A., 2015, July. Current maize production, postharvest losses and the risk of mycotoxins contamination in Tanzania. In *Agricultural and Biosystems Engineering Conference Proceedings and Presentations*.

artisans throughout Uganda to design the metal silos. Please refer to the comprehensive report for more details regarding the project.


POST HARVEST FARMING EQUIPMENT
(WORLD FOOD PROGRAMME ORDER DOCUMENT)
DATE ……………………………………
NAME OF FARMER ……………………………………… NAME OF FARMER ORGANISER……………………………………………………
DISTRICT……………………………………………… SUB-COUNTY……………………………………….. PARISH……………………………………

SUPER GRAIN BAGS (80KG / per bag)
OPTION 1a.
4 Bags + 1 Plastic Sheet
Total = Sh 65,000
Farmer to pay ⇨ Sh 19,500
OPTION 1b.
4 Bags + 2 Plastic Sheets
Total = Sh 102,000
Farmer to pay ⇨ Sh 31,000

PLASTIC SILO (250KG / per silo)
OPTION 2a.
1 Silo + 1 Plastic Sheet
Total = Sh 147,000
Farmer to pay ⇨ Sh 44,500
OPTION 2b.
1 Silo + 2 Plastic Sheets
Total = Sh 185,000
Farmer to pay ⇨ Sh 56,000

METAL SILO /medium (530KG / per silo)
OPTION 3a.
1 Silo + 1 Plastic Sheet
Total = Sh 393,000
Farmer to pay ⇨ Sh 118,000
OPTION 3b.
1 Silo + 2 Plastic Sheets
Total = Sh 430,000
Farmer to pay ⇨ Sh 129,500

METAL SILO /large (1300KG / per silo)
OPTION 4a.
1 Silo + 1 Plastic Sheet
Total = Sh 550,000
Farmer to pay ⇨ Sh 165,000
OPTION 4b.
1 Silo + 2 Plastic Sheets
Total = Sh 587,000
Farmer to pay ⇨ Sh 176,500

Farmers must only select ONE option

Figure 1: SO1 equipment order sheet. "Farmer to pay" = subsidized prices; "Total" = unsubsidized prices.

Approach

CITE has conducted several comparative evaluations of product alternatives that support international development initiatives. A common CITE approach has been to identify key criteria, define appropriate metrics, and apply weights to the metrics in calculating a score for each product alternative. For this study, we used a different approach to evaluate the scalability of storage technologies. Instead of a static score for the scalability potential, we developed a model to project adoption over time based on key factors in the market system. The model is a useful alternative to a static score since it shows the dynamics of scaling over time, enables sensitivity analysis for key factors, and allows for evaluation updates based on actual performance.

To identify and quantify key factors in the model, we conducted field research using the lens of embedded supply chains. In this case, the supply chains for crop storage technologies play a role in the effectiveness of the crop supply chains. Figure 2 depicts key roles in both supply chains (e.g. distributors, agro-dealers/retailers; farmers, market traders) and the key actions they take (noted by italics in the figure, e.g. manufacturing, stocking; harvest, storing). The intersection is the point at which a farmer decides whether or not to buy a storage technology; the technology adoption point. Technology adoption increases when supply chains can make affordable products readily available. It also increases when potential adopters anticipate the opportunity for increased income, and a positive impact on their well-being, through participation in the crop supply chain.

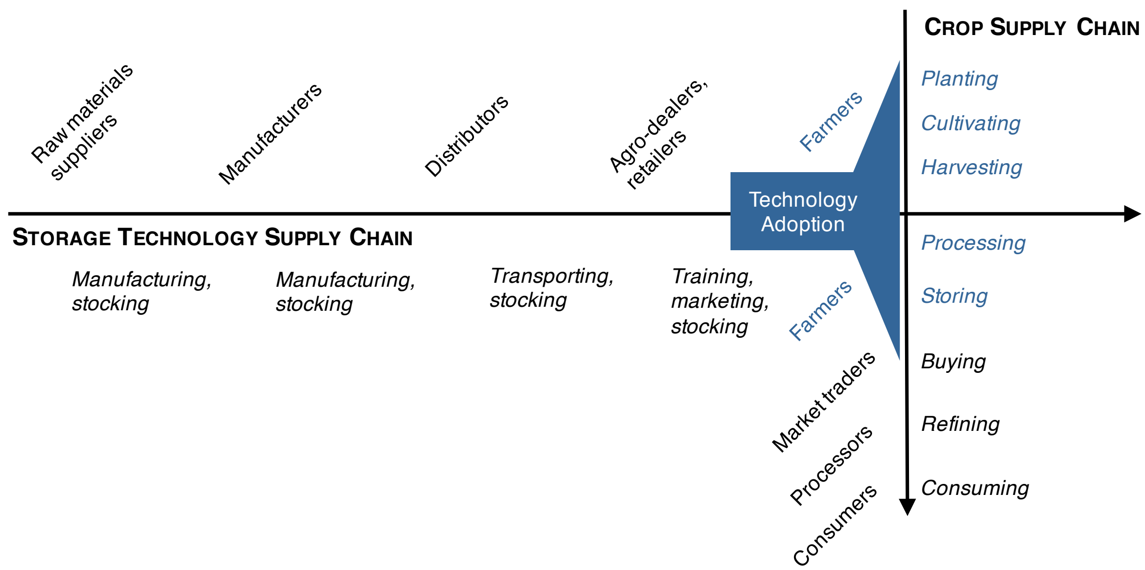


Figure 2: Framework of embedded supply chains in this study

We conducted a survey of 153 adopters, randomly selected from among the farmers who purchased a storage technology in SO1, to assess the farmer impact on various factors. We used regression models to analyze the change in income, food security, and socio-economic well-being for adopter households. To measure the willingness to pay for each storage technology, we further surveyed 49 non-adopter farmers, selected on a random walk in the adopters' communities, for a total of 202 respondents. The gender demographics of this study were very similar to the overall WFP Special Operation, where women represented 62% of the 16,600 farmers who participated. Women comprised 95 respondents (62%) in the random sample of adopters and 31 respondents (63%) from the random walk of non-adopters. Gender did not seem to play a role in the technology adoption decision. Among adopters in the study sample, the final decision to buy the storage technology was evenly distributed among the husband (31%), wife (31%), and both husband and wife (35%), with 3% decided by the whole family.

To assess the affordability and availability of equipment, empirical data for cost structures and capacities were gathered through a two-stage, semi-structured interview with all supply chain actors directly engaged in the SO1 project: six metal artisan firms, two sheet metal importers, one plastic silo manufacturer, one crop bag importer, and one transportation firm. The first stage comprised detailed process mapping of that actor's operations; the second stage validated cost and capacity parameters. To focus on scalability over time, the analysis considered the current state and potential opportunities for improvement.

Scalability was assessed using a Bass diffusion model, which is a classic approach to project the adoption of new products in a market. Supply chain flows can be modeled using the same system dynamics methodology. Thus, we were able to incorporate empirical farmer and supply chain data in a single, integrated model (see Figure 4 below). The system dynamics model simulated adoption of storage technologies over a 10-year time horizon under various scenarios. Scenarios enabled sensitivity analysis of key inputs and assumptions for all four technologies: hermetic crop bags, plastic silos, medium metal silos, and large metal silos.

Farmer Impact

Despite increasing efforts to address post-harvest losses among smallholder farmers through use of hermetic storage technologies, there is little research regarding the impact on and value to farmers. Bokusheva, et al. (2012) studied the reasons for and impact of adopting metal silos in in Guatemala, Nicaragua, Honduras, and El Salvador following the Postcosecha Programme supported by the Swiss Agency for Development and Cooperation (SDC).[7] They conducted a survey of 1,600 households from El Salvador, Guatemala, Honduras and Nicaragua and used regression models to assess the impact of adopting the silos. Compared to the silo non-adopters, the adopter households experienced a significant improvement in their food security and well-being, though the impact of their adoption varied across the four countries. Our analysis followed their approach to contribute the first evidence from the African continent regarding the farmer impact of improved storage technology adoption.

The survey results showed positive impact of storage technology adoption in all three areas of focus – farmers' income, food security, and socio-economic well-being. Regarding income, the maize sales price was higher ($p<0.01$) for the improved technologies relative to both no storage and traditional storage approaches. Food security improved as storage technology adoption reduced external purchasing for maize by 1.51 months ($p<0.01$) and beans by 0.90 months

[7] Bokusheva, Raushan, Robert Finger, Martin Fischler, Robert Berlin, Yuri Marín, Francisco Pérez, and Francisco Paiz. 2012. "Factors Determining the Adoption and Impact of a Postharvest Storage Technology." Food Security 4 (2): 279–93.

($p<0.05$). Finally, various socio-economic conditions improved for technology adopters as their responses were nearly a full point lower on a five-point scale where *1=much better over the past* year and *5=much worse over the past year*. The adopters' improvement was statistically significant ($p<0.01$) for the following variables: food availability (0.88 improvement on the five-point scale), household health (0.74), sons' schooling (0.72), daughters' schooling (0.72), women's workload (0.85), family income (0.91), women's socio-economic status (0.88), men's status in the community (0.82), and women's status in the community (0.83).

Farmer Willingness to Pay

The impacts above inform the perceived value to adopters and their non-adopter neighbors. We measured this value directly by asking survey participants, both adopters and non-adopters, about their willingness to pay for each technology, using the original order sheet with subsidized and unsubsidized prices as a reference. Figure 3 shows the results for each technology: at 0 USD, 100% of farmers would be willing to "purchase" the technology. As the price increases, the percent willing to pay decreases until it reaches a price at which no farmer would purchase the product. There was a sizable portion of the population who were willing to pay above the subsidized price, but below the unsubsidized price. Though not depicted separately in Figure 3, the willingness to pay was higher among non-adopters at almost every price level for all products. This may be an indicator of perceived positive impact among adopters traveling by word-of-mouth communication, which is a key factor in scalability.

Though most of the "demand curves" in Figure 3 look similar, the willingness to pay for plastic silos was slightly higher. At both the unsubsidized and subsidized prices the plastic silos had the highest percent willing to pay. In addition, for prices up to 35% higher than the subsidized price, the plastic silo demand tracked much higher than other products. This could indicate that they provide good value for the farmer's investment or that prices for the SO1 launch were slightly low relative to other technologies.

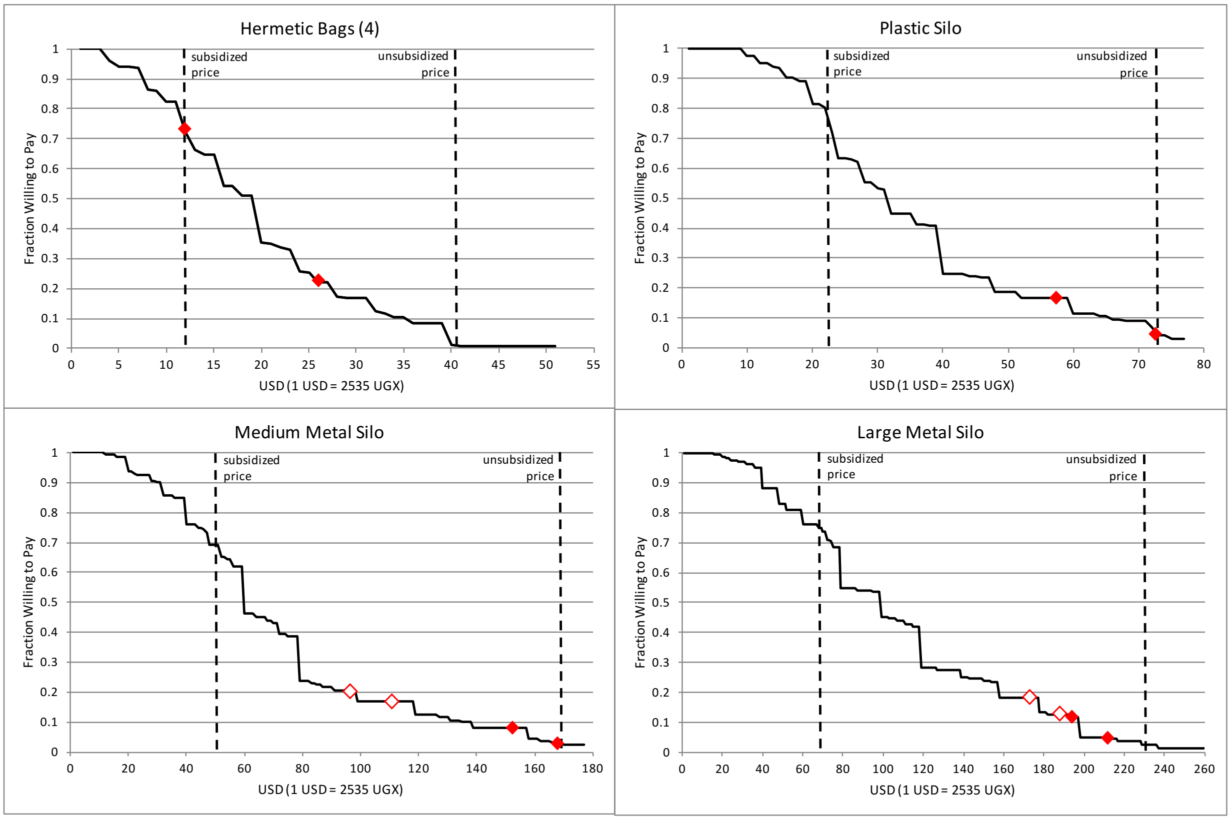


Figure 3: Willingness to pay, by storage technology (price includes 2 plastic sheets). Two projected prices are included on each plot as solid points: the lower price is just the equipment, the higher price includes 2 plastic sheets), Hollow points on metal silo plots represent the artisan with the lowest projected price.

Supply Chain Cost and Capacity

Profit margins are a critical measure for the scalability of the supply chain – clearly affecting affordability, but also availability since actors are less likely to invest in capacity for low margin items. We analyzed margins using the unsubsidized prices established during SO1. The suppliers for metal silos had positive margins for both large (11.8%) and medium (4.1%) sizes. The bag supplier margin could not be determined since the team did not visit the firm's manufacturing site in Asia to conduct cost analysis. The most concerning observation was that the plastic silo supplier lost $9.60 per silo (-25.3% gross margin), with a manufacturing cost that alone exceeded the SO1 full retail price.

Gross profits for the sales channel, which incorporates all activities following finished good production though the sales transaction such as transportation and training, ranged from $5.39 to $21.89 per silo (7-14% gross margin) and were slightly negative for the bags (-$0.07 per bag,

-2.6% gross margin). These profit levels cannot support the average training cost of $22.25 per farmer paid during SO1, much less the transportation cost that was also covered separately. Regression analysis of the training operations for various organizations showed that cost was highly dependent on the number of farmers trained.

Manufacturing capacity was assessed by on-time delivery for the production schedules set by manufacturers for the transportation provider. Bag availability was very good, with only 4% of the required products missing shipment schedules. Plastics silos performed nearly as well with only 6% shortfall. In contrast, the metal silo suppliers struggled to meet requirements with 24% of the medium and 53% of the large silos falling short of scheduled delivery. More detailed cost structure and capacity analysis are available in the comprehensive report.

For a fair comparison of scalability going forward, we applied the same profit margin assumptions[8] to each technology to calculate a projected price. The calculations and comparison with the SO1 full retail (unsubsidized) price are shown in Table 1. The cost structure for metal silos was reasonable with projections 3% below the SO1 price for large silos and 10% higher for medium silos. Using the minimum cost among the six artisans revealed an opportunity to maintain good margins while reducing the metal silo retail price by 14-30%. Cost structures for plastic silos and hermetic bags, each of which relied on data from the single supplier, were not as promising. Significant cost reductions would be required for plastic silo production, which projects to be 35% above the SO1 price. Such a large gap may indicate the need for a new business model or product design. The 16% price premium for bags may potentially be addressed by adapting existing models and designs to make large efficiency gains.

These projected prices are also plotted in Figure 3 to indicate the potential market share they could enable.[9] It is important to note that the projected prices were not based on supplier bids, which could be distorted by on a firm's desire to win a particular contract; they were "bottom up" calculations based on empirical cost structure and process analysis.

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[8] We assumed a supplier margin of 8%, which is the midpoint between medium and large silo margins for the metal artisans. The pre-tax margin for several related sectors (Machinery, Packaging & Container, Diversified) in emerging markets is also around 8%, as documented in a widely referenced database from the Stern School of Business at New York University (http://www.stern.nyu.edu/~adamodar/New_Home_Page/data.html). Though retailers and distributors typically have lower margins than manufacturers, we assumed a higher margin of 12% for the sales channel for several reasons: it is in line with the 7-14% gross margin for silo sales channels in the Special Operation, channel profits may need to support the profitability of more than one actor, and the farmer training was time-intensive but should be supported.

[9] Two price points were plotted on each chart, since the survey question regarding willingness to pay did not explicitly include two plastic sheets, though prices referenced on the order sheet included the plastic sheets.

Table 1: Projected retail prices. (Note: metal silos have both the average supplier cost among the six firms and the minimum cost for the same sample.)

	Supplier Cost	Supplier Gross Margin	Supplier Price	Channel Gross Margin	Projected Retail Price	SO1 Full Retail Price	Percent of SO1 Price
Metal Silo Large (average)	$ 158.73	8%	$ 172.53	12%	$ 196.05	$ 201.84	97%
Metal Silo Medium (average)	$ 124.65	8%	$ 135.49	12%	$ 153.97	$ 140.04	110%
Metal Silo Large (minimum)	$ 141.29	8%	$ 153.58	12%	$ 174.52	$ 201.84	86%
Metal Silo Medium (minimum)	$ 79.22	8%	$ 86.11	12%	$ 97.85	$ 140.04	70%
Plastic Silo	$ 47.60	8%	$ 51.74	12%	$ 58.79	$ 43.39	135%
Bag	$ 2.48	8%	$ 2.70	12%	$ 3.06	$ 2.63	116%
Bags (4)					$ 12.25		
Tarps (2)						$ 14.60	

Scalability

Scalability was assessed using a classic model to project the adoption of new products. The system dynamics model combined a Bass diffusion sub-model, where potential technology adopters become actual adopters via social and/or marketing dynamics, and a supply chain sub-model, which incorporates technology availability as a constraint on the adoption rate. To calibrate parameters, we combined evidence regarding impact and willingness to pay for these technologies with our analysis of the associated supply chains. Figure 4 shows the structure of the model, highlighting in blue the components that were altered for scenarios.

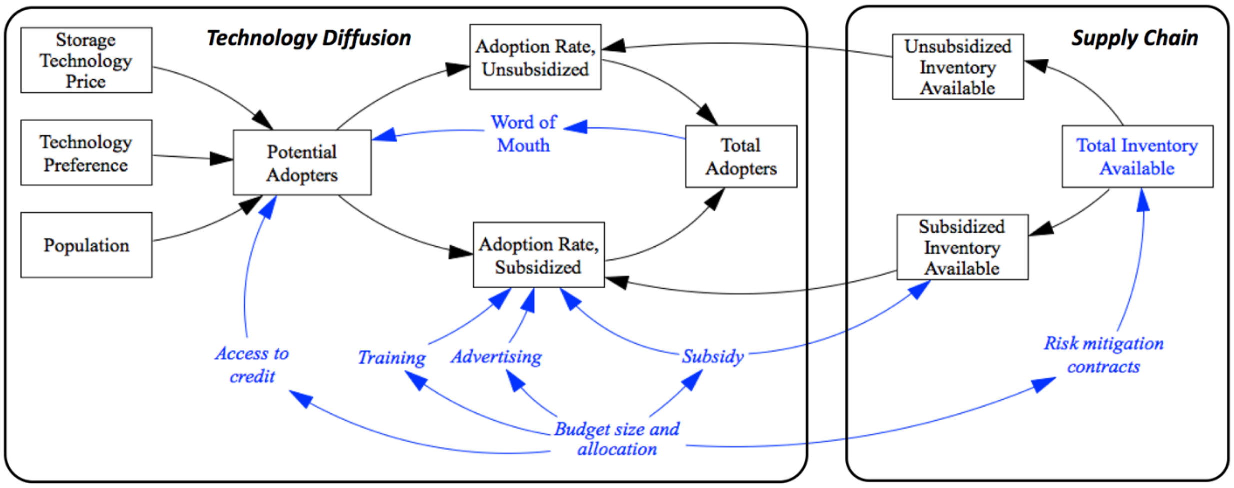

Figure 4: Model structure (given model components, black; scenario model components, blue)

Model results show that total adopters for the baseline case, which is based on the SO1 full retail prices and not the projected prices from Table 1, grew initially before tailing off in the latter half of the horizon; the total over all four technologies reached 1.05 million households (17.5% of the total) by 2024. Figure 5 breaks down the adoption by technology. Plastic silo adoption outpaced other technologies, driven by two key factors. First, as noted earlier, the willingness to pay for plastic silos based on SO1 prices was higher than the other technologies. Second, and more important, the plastic silo manufacturer had higher inventory levels to accommodate the attractive value proposition for farmers under the subsidy.

Scenario analysis pointed to inventory, access to credit, and word-of-mouth contact as having a stronger positive impact on adoption, while higher budgets for advertising and training did less to yield greater adoption. Focusing on affordability, a 5% annual price reduction from 2015 to 2024 resulted in 1.19 million adopters (20% of the total). Availability had a bigger impact, as doubling inventory alone resulted in 1.55 million adopters (26%). While lower price alone has a positive impact on adoption, higher inventory is required to capitalize on the opportunity. Leveraging this insight, we compared the baseline ten-year subsidy with a “strong supply chain” scenario that phased out the subsidy over five years but added 3% annual price reductions and 10% higher inventory. While the strong supply chain scenario tracked slightly behind the baseline in the early years, as its subsidy was phased out faster, it maintained steady growth trajectory over the ten-year horizon, resulting in a total adoption of 1.37 million (23% of the market).

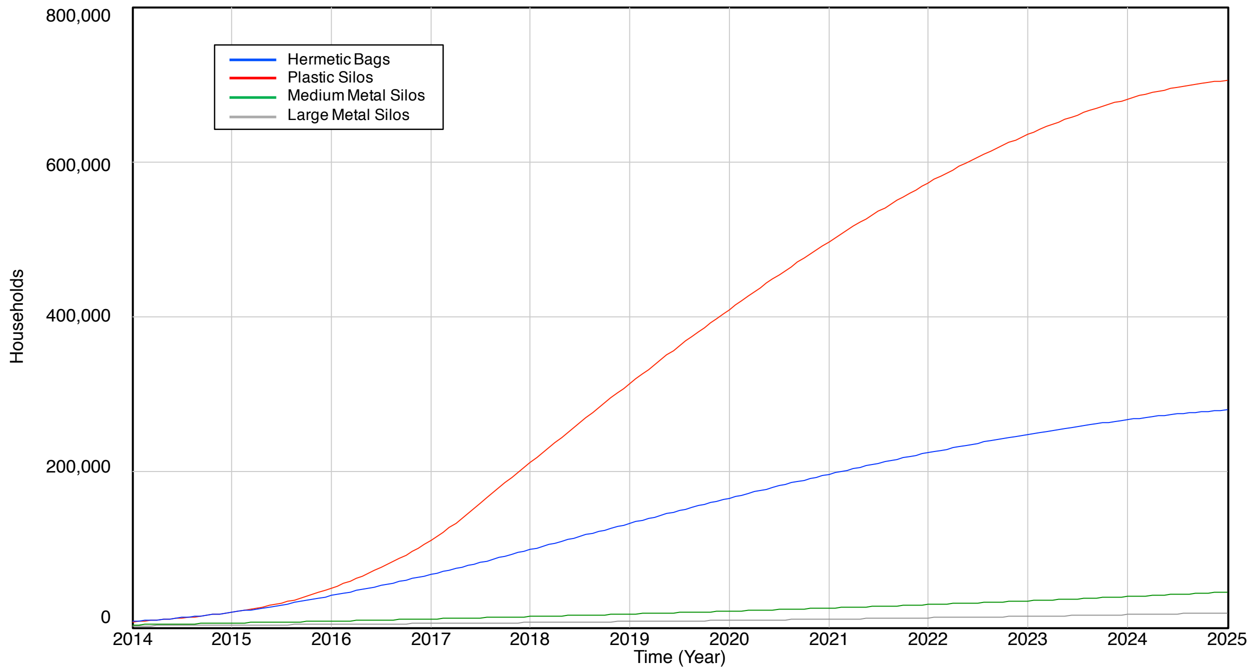

Figure 5: Baseline scenario, adopters by storage technology

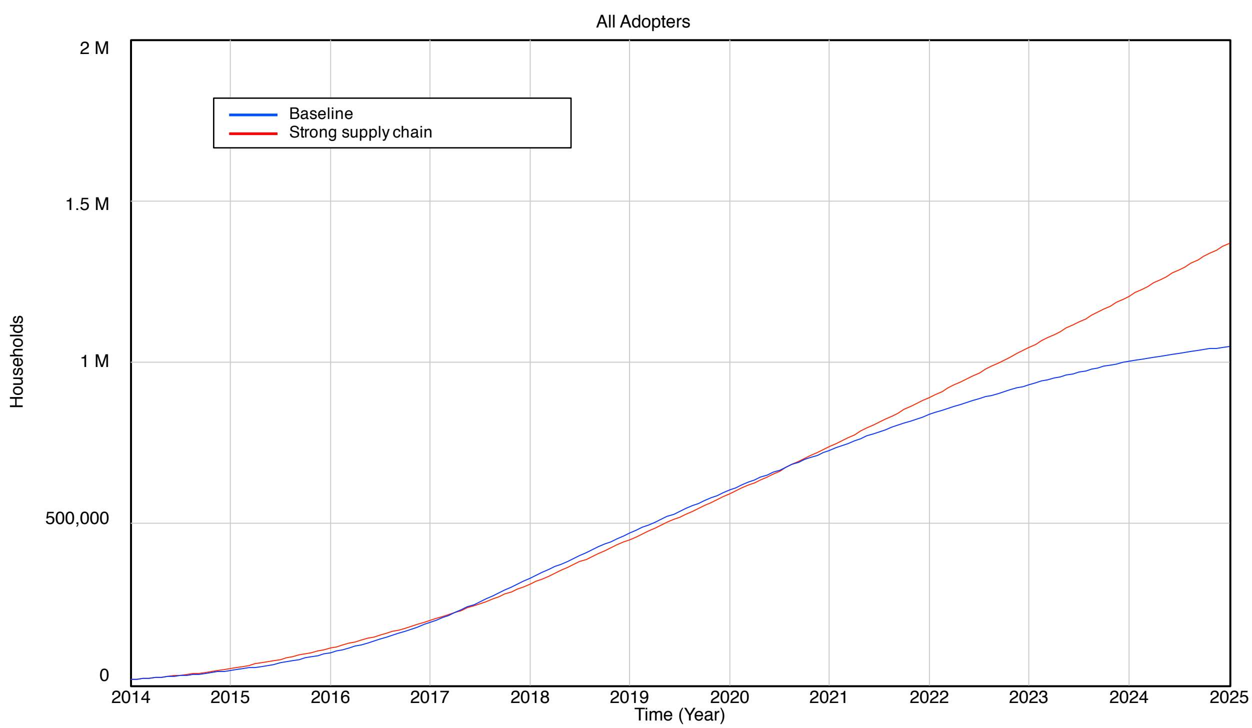

Figure 6: “Strong supply chain” and baseline scenarios, total adopters

Key Findings and Recommendations for Storage Technology Adoption

Three high-level findings emerge from this study of storage technology adoption in Uganda.

1. Storage technology adoption had a positive impact on farmers' livelihoods. Similar to previous studies in Central America, storage technology adopters in Uganda reported a significant improvement in income, food security, and socio-economic well-being (e.g., household health, children's education, women's workload, status in the community). As households begin to consume more of the food they harvest and store, reduced food expenses enable financial flexibility to address other needs. Storage technologies also contribute to financial stability since grains can be sold incrementally throughout the post-harvest season. Hence, it was not surprising to observe improvement in areas such as children's education, as grains are often a suitable form of tuition payment, and women's workload, as storage technology reduces daily efforts to gather grains for consumption that are typically undertaken by women. This study contributes to the evidence base showing a significant impact of storage technologies on smallholder farmers' livelihoods, and we recommend further efforts to facilitate storage technology adoption.

2. Supply chain strengthening offered a better foundation for storage technology adoption than longer-term subsidies. Results from the system dynamics model grounded in data from SO1 showed that an approach that strengthens supply chains (modest cost reductions and increased inventory) while phasing out subsidies early facilitated more adoption than the ten-year subsidy. While reduced subsidies slowed adoption in the early years, supply chain improvements were able to sustain adoption growth over the time horizon, resulting in 23% market penetration compared with 17.5% for the ten-year subsidy. We recommend a shift in resources away from subsidies and toward efforts to understand and improve supply chains.

3. The nascent supply chain for each storage technology had shortcomings but also opportunities for improvement.

It is not surprising that the supply chains supporting new products have room for improvement. Our analysis highlighted the most critical gaps and some promising opportunities among the technology options. Since supply chain strengthening to reduce cost structures and increase capacities is critical for long term adoption, we recommend a focus to facilitate the following business model improvements:

a. **Pursue lower cost structures for all technologies.** Willingness to pay results indicate the importance of cost reductions for each storage technology to improve market penetration. This is particularly true for the current plastic silo manufacturer, which had negative gross margins. Several opportunities to improve costs for these nascent supply chains, which should be pursued in combination, were identified. First, incremental changes in production and distribution processes offer many cost reduction options at this early stage in a product launch. Second, larger sales volumes could offer cost reductions through economies of scale. Third, new business models, new vendors, and/or new product designs could offer "step change" opportunities to dramatically lower prices to farmers. Finally, it is important to remember that public policy can have an important impact on cost structures, especially changes in tax policy.
b. **Analyze the potential for skilled workers and equipment to increase local artisan capacity.** While metal silo artisans struggled to meet delivery requirements during their initial year of production, we observed opportunities to improve local production capacity, which facilitates rural economic development and reduces transportation cost for bulky metal silos. Though based on a small sample, data showed that firms employing higher skilled labor and investing more capital in equipment had higher productivity. Further study is needed to understand the value of training laborers with specific skills and to identify the most cost-effective deployment of manufacturing equipment.
c. **Develop approaches to reduce the variable cost to reach and train farmers.** Training was costly and directly proportional with the number of farmers. This consultative sales model is especially challenging for hermetic bags, with gross profits that are much lower than for silos. Opportunities identified include a different model for direct training, increasing the use of radio promotion, and the potential to leverage existing retail networks that serve farmers.

4. Explore issues of trust with buyback contracts that could improve product availability among risk-averse supply chain actors. Buyback contracts have the potential to mitigate innate reluctance to invest in inventory, a risk-avoidance behavior documented in a West African study of storage technologies. However, our behavioral experiment indicated more aversion to operational risk when mitigated by contracts than the general risk profile as revealed by a standard risk lottery experiment. Further, the results differed based on the contract type, indicating less trust in contracts that applied to finished goods than to raw materials.[10] Risk mitigation mechanisms may be critical for making products available to farmers and deserve further study.

[10] For these results, see Castaneda, J, Brennan, M., and Goentzel, J. "Supply Chain Contract Design for a Newsvendor Problem in a Developing Economy." Working Paper, April 2016.

General Recommendations for Scaling Technology Adoption

Some lessons drawn from this study are generalizable beyond crop storage technologies and contribute to better evaluation of and design for scalability.

1. Willingness to pay results are critical in designing the "go-to-market" strategy for product adoption. Willingness to pay results from this study offered a useful reference point for the market value of products in designing further strategies to meet the demand. For example, the higher value of plastic silos relative to the SO1 price illustrates the importance of appropriate pricing, especially given data that the price did not cover the manufacturer's costs. Market-based prices drive accurate target costs that are critical for product and supply chain design. In addition, higher willingness to pay among non-adopters in the adopter communities points to strong communication of the value proposition by word-of-mouth. Understanding the potential of such relationships in the marketplace is critical in developing promotion and training strategies. We recommend that consumer or end-user surveys incorporate questions that enable a (stated preference) contingent valuation approach for estimating willingness to pay.

2. Multi-year facilitation support from a development organization provides opportunities to analyze and improve supply chains, which are critical for technology adoption. While strong supply chains are critical for technology adoption over the long term, operational facilitation from development organizations can be important in early stages. The WFP support enabled enough operational scale in SO1 to effectively identify cost and capacity improvements. This facilitative approach can have a similar effect as directly subsidizing products or production capacity but encourages more co-creation with the private sector. This approach relies on deeper engagement in analyzing operational processes (e.g. production, transportation, sales channel) and monitoring improvement to effectively ramp down facilitation support. Evidence from this study indicates that with iterative operational facilitation to realize key improvement opportunities, supply chains for hermetic crop storage technologies can scale beyond previous pilots. We recommend that development organizations pair multi-year facilitation of technology adoption with operational analysis to improve supply chains.

3. A mixed methods approach including empirical research and modeling enables better characterization of the system and identification of insights for scalability. This study used various empirical methods (e.g., surveys, semi-structured interviews, process mapping, behavioral experiments) and modeling approaches (e.g., regression, contingent valuation, system dynamics) to capture and characterize the system for storage technology adoption.

Models have the potential to continually add value by incorporating new empirical data and evaluating new scenarios. For example, the system dynamics model developed for this study could be used to calibrate future facilitation efforts by quantifying targets for manufacturers' costs or farmers' access to capital. We recommend deployment of mixed research methods to evaluate and design international development programs.

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