



# The economics of reducing food losses: Experimental evidence from improved storage technology in India

Pallavi Shukla<sup>a,\*</sup>, Hemant K. Pullabhotla<sup>a</sup>, Kathy Baylis<sup>b</sup>

<sup>a</sup> Department of Economics, Deakin University, Burwood, VIC 3125, Australia

<sup>b</sup> Department of Geography, University of California, Santa Barbara, CA 93117, United States

## ARTICLE INFO

### Keywords:

Economic losses  
Food security  
Improved storage technology  
Auction

## ABSTRACT

Understanding the economics of food loss-reduction technologies is crucial to promote their adoption. We offer experimental evidence on returns to technology that studies a wide range of food security outcomes and accounts for the quality, quantity, and economic gains from adoption. Using two randomized experiments on improved storage with farmers in India, we find that food loss-reduction technology delivers large gains on multiple aspects of food security. The largest benefits of loss-reduction technology come from reduced quality and economic losses. Using a novel within-farmer experiment, we offer evidence of significant economic incentives for investing in loss-reduction technology in local rural markets. Our cost-benefit analysis shows that farmers recover the full unsubsidized cost of the reusable improved storage technology in one agricultural season.

## 1. Introduction

Most scholars agree that reducing food losses is an important strategy for achieving a more sustainable and food secure future. The Food and Agricultural Organization estimates that 13.8 percent of food produced yearly is lost before reaching the retail stage (FAO, 2019). Postharvest losses can account for a large share of total food losses, particularly in developing countries with inadequate public and private storage infrastructure. Recent studies evaluate the effectiveness of various postharvest loss-reduction technologies across countries (Stathers et al., 2020). Among others, on-farm drying and improved storage technologies were found to effectively reduce postharvest losses in food grains (Brander et al., 2021; Magnan et al., 2021; Pretari et al., 2019; Omotilewa et al., 2018; Abass et al., 2018; De Groote et al., 2013).

While the evidence on the effectiveness of loss-reduction technologies is promising, we identify two key areas for improving the evaluation of such technologies. First, studies trying to estimate the benefits of loss-reduction technologies often focus only on measuring some aspects of food security. Food security is a multidimensional measure, and evaluating the full impact of loss-reduction technologies requires measuring the effect of technology on each dimension of food security. For example, multiple studies look at how a loss-reduction technology like improved storage or drying sheets can help farmers reduce quantity losses, store more grains for longer durations, and reduce aflatoxin

contamination (Brander et al., 2021; Bauchet et al., 2021; Magnan et al., 2021; Aggarwal et al., 2018; Omotilewa et al., 2018; Basu and Wong, 2015; for non-experimental evidence, see Tesfaye and Tirivayi, 2018; Gitonga et al., 2013; Bokusheva et al., 2012). While these are important measures of food security, estimating the full benefits of a loss-reduction technology on food security requires measuring the impact of technology adoption on all indicators of food security in one study context.

Second, few evaluations of loss-reduction technologies study the economics of reducing food losses. The economics of reducing food losses include understanding returns to technology and a comprehensive economic cost-benefit analysis that accounts for quality, quantity, and financial losses in the absence of loss-reduction technologies. Sheahan and Barrett (2017) emphasize that discussion about economic incentives for reducing postharvest losses is often missing from the debate on food loss reduction strategies. Recently, there has been growing recognition of the need to measure quality and economic losses (Affognon et al., 2015; Cattaneo et al., 2021; Delgado et al., 2021). In two studies that investigate economic incentives for reducing food losses, researchers have found that food losses are either economically insignificant or the cost of loss-reduction technologies outweighs its benefits (Anriquez et al., 2021; Chegere, 2018). Loss-reduction technologies will remain unadopted if there are no incentives in the food supply chain to preserve grain quality. Subsidizing and advocating for the adoption of loss-reduction technologies without considering economic returns to

\* Corresponding author.

E-mail addresses: [p.shukla@deakin.edu.au](mailto:p.shukla@deakin.edu.au) (P. Shukla), [h.pullabhotla@deakin.edu.au](mailto:h.pullabhotla@deakin.edu.au) (H.K. Pullabhotla), [baylis@ucsb.edu](mailto:baylis@ucsb.edu) (K. Baylis).

<https://doi.org/10.1016/j.foodpol.2023.102442>

Received 17 November 2021; Received in revised form 2 March 2023; Accepted 12 March 2023

Available online 19 April 2023

0306-9192/© 2023 Elsevier Ltd. All rights reserved.

adoption offers little benefit.

We contribute to these two key areas by studying the impact of loss-reduction technology on a wide range of food security outcomes and conducting an economic cost-benefit analysis for a loss-reduction technology. We provide experimental evidence on the impact of an improved storage technology on economic losses, investigate financial incentives for adoption, and estimate gains in overall food security from adoption. We conduct two field experiments with smallholder maize, wheat, and rice farmers in India. In the first experiment, we randomize access to improved storage to farmers at subsidized prices using a random price field auction. We conduct a second experiment with a subsample of farmers to estimate economic losses and financial incentives for adopting technology. In this within-farmer experiment design, each farmer stores maize in two improved and two traditional storage bags over four months. The farmers then sell one bag of each kind separately to the same trader after two months and then again after four months. The variation in price received for grains stored in improved versus traditional storage helps us understand the economic losses and associated financial incentives to reduce those losses. Finally, we conduct a detailed cost-benefit analysis of improved storage technology for smallholder farmers.

Our findings suggest that treatment group farmers experienced nearly no physical grain losses due to fungal, rodent, or pest damage during storage compared to the control group farmers. Using improved storage technology decreased the incidence of toxic contaminant aflatoxin by around 75 %. After harvest, farmers with access to improved storage were significantly more likely to store a larger share of their production (~20 % more) for longer durations (~25 % longer), facilitating consumption smoothing over seasons and income shocks. Improved storage had a positive impact on grain marketability. Treated farmers experienced a 30 % increase in the likelihood of selling grains in the market a few months after harvest, suggesting possible arbitrage. We also find evidence of substitution away from more expensive market-purchased grains to own stocks for household consumption. For the treatment group, consumption of staples from own stocks increased by around 20 %, and that from market sources decreased by 8 %. This is an important cost-saving measure for low-income households that spend much of their income on food.

We find that improved storage reduces economic losses and offers significant financial incentives for farmers to adopt the technology. Grain stored in improved storage received, on average, 13 % higher prices in local markets than in traditional storage. Our benefit-to-cost analysis suggests that conservatively, farmers recover the full unsubsidized cost of the (reusable) storage technology in one agricultural season. We show that evaluations of loss-reduction technology that focus only on quantity fail to capture over 60 to 70 % of the benefits of technology.

In the following sections, we present a theory of change on how loss-

reduction technology impacts food security, quantity, quality, and economic losses. We then present the experimental design for both experiments and estimation strategy, followed by our findings and their policy implications.

## 2. Theory of change

Broadly defined, the four pillars of food security are availability, access, utilization, and stability (Food and Agriculture Organization, 1996). Availability captures the physical availability of food - not just in terms of quantity but also quality. Access refers to economic access and affordability of food, determined by local food prices and household income. Utilization refers to food safety - the use of safe food in a manner that provides the required nutrients to the body for a healthy life. Finally, stability implies continued access to safe and healthy food at all times and the ability to smooth consumption over different income shocks.

Fig. 1 shows the hypothesized channels through which improved storage can affect food security. Reducing storage losses due to spoilage, pests, and rodent damage increases the amount of grain available for sale and household consumption. Storage in hermetic bags retains grain quality for longer and provides benefits that are twofold: not only does it provide arbitrage opportunity to farmers to sell later when prices are higher, it also provides them the option to store grain for their own consumption eliminating the need to buy back from the open market later at higher prices. This ability to arbitrage over time can be both directly profitable and cost-saving for smallholders and provides a means to store grains for the lean season.

Improved storage will also improve food safety. As past research findings suggest, improved storage or drying limits the growth and spread of aflatoxin contamination in the short term (Williams et al., 2014; Mutungi et al., 2016; Bauchet et al., 2021; Magnan et al., 2021; see Leavens et al., 2021 for long-term effectiveness). Gitonga et al. (2013) found that farmers who had access to better storage technology also used less pesticide during storage. Both these factors contribute to improved food safety and nutrition measures by reducing exposure to toxins that compromise animal and human health.

The aggregate effect of increased quantity available for consumption and sale, higher market prices, improved nutrition, and longer storage duration has an overall impact on improving food security. When we fail to capture the impact of food losses on any of these aspects of food security, we underestimate the impact of food losses. Similarly, when we fail to capture the impact of loss-reduction technology on any of these dimensions of food security, we underestimate the benefits of that technology.

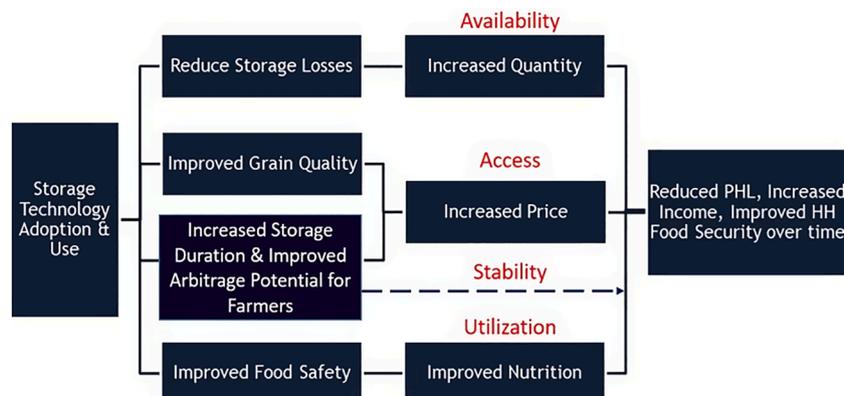


Fig. 1. Theory of Change.

### 3. Experimental design

In the following sub-sections, we provide details of the study area, background on the hermetic bag technology, and the design of both experiments – the auction experiment and the storage and sales experiment.

#### 3.1. Study area

We conduct our study with a sample of farmers drawn from the eastern state of Bihar in India. According to 2012 estimates, Bihar is one of India's poorest and the third most populous state, with over 33 percent of the population living below the government estimated poverty line (RBI, 2013). On average, farmers in our sample have an average annual per capita income of about USD 230, and 83 percent have less than one hectare of farmland. Around 90 percent of the cropped area is under food grains, with rice, wheat, and maize being the main crops. Fig. A1 in the Appendix shows a map of our study area. Five study districts were chosen in consultation with partner research agricultural universities in the state. In the first two districts, six villages each, and in the third and fourth districts, seven villages each were randomly selected from the list of census villages with a population between 100 and 500 households. In the fifth district, 16 villages within the same population range were randomly selected from the census list. We oversampled villages in the fifth district for use in a separate experiment in which we implemented a second round of auctions. This additional intervention was carried out after the end of the current study. We conducted a rapid listing of households within the selected villages, and 50 households were randomly sampled for the auction experiment. This gave us a sample of 2100 households in 42 villages.

#### 3.2. Improved storage technology

We used GrainPro SuperGrain bags of 50 kg (110 lbs.) capacity each and restricted the number of bags available for purchase to a maximum of five bags per farmer. These GrainPro bags are made from multilayer recyclable polyethylene plastic with an additional barrier layer. Once filled, the bags are closed tight using simple cable ties. After storage, a depletion of oxygen and a buildup of carbon dioxide occurs due to respiration by the grain, fungi, insects, and other microorganisms present within the bag (Somavat et al., 2017).

The full market price of the 50 kg (110 lb.) hermetic bags at the time of the experiment was USD 1.20 or INR 80. In comparison, traditional jute bags used for grain storage cost about INR 10. At baseline, hermetic bags were not available for purchase in any of the sample villages, and none of the farmers in the sample were aware of the technology.

#### 3.3. Experiment 1: Auction experiment

Our first experiment employs a Becker-DeGroot-Marschak (BDM) auction to measure farmers' willingness to pay (WTP) for improved storage technology and assigns them to either treatment or control. Instead of a simple randomized assignment to treatment and control, we chose to implement a BDM auction because, in addition to measuring the impact of improved storage, we also wanted to understand the willingness-to-pay (WTP) for improved storage across the distribution of prices. While this study only uses WTP as control variables, our associated work from the same study area uses the WTP measures from this experiment to study the impact of anchoring effect from the initial price paid on long-run WTP (Shukla et al., 2022). State-level policymakers in the study area and funders of this project wanted to understand the market for improved storage and the level of subsidy needed to promote technology adoption. Thus, we decided to use a BDM auction design that would reveal the local farmers' WTP for improved storage.

The BDM mechanism was implemented as a single-buyer, single-seller auction. The auctions were implemented separately for each

individual participant, usually at the residence of the participant by a field enumerator. Our team of 26 field enumerators completed the auction in each village in one day to avoid any strategic interaction between farmers during or after the auctions. All field enumerators followed a uniform information and auction implementation script. The script used to provide information about the hermetic bags and implement the auction is provided in Appendix B. Broadly, field enumerators carried out four steps for this experiment: (a) explain the use and benefits of improved storage technology, (b) explain the auction process verbally and by simulation, (c) conduct the auction of hermetic bags, and (d) help farmers store grains in hermetic bags.

In the first step, the field enumerator explained how improved storage technology works and the benefits of storing grains in a hermetic bag. They then provided information about how to store grains safely (i. e., proper drying before storage, ensuring drying and storage areas are clean, no scattered grains on the floor of the storage area which may attract rodents, etc.). They also had a sample of a hermetic bag that the farmer could examine closely. The enumerator then asked the participant if they understood the technology and if they had any questions. Once the farmers were satisfied and had no questions, the enumerator moved to the second step.

In the second step, the field enumerator explains how the BDM auction works, first verbally and then by simulation. We used two small packs of cookies of INR 5 each for the simulation and only proceeded to the actual bag auction once the farmer understood the mechanism. The farmers were informed that the auction could only be conducted once and that the result would be binding. Once the farmer agrees, the enumerator moves to the third step, which is the WTP elicitation process or auction.

To elicit their WTP, the enumerator starts by asking each farmer if he is willing to purchase the technology at the price of INR 10 (the lowest offer price). If the farmer says yes, the enumerator goes to the next price point and asks them if they would purchase the technology at INR 15. This process continues until the farmer says no to purchasing at a price point. Note that the farmer's revealed preference WTP is the maximum price at which they were willing to purchase at least one bag. For instance, if farmer A says yes to purchase at INR 10, 15, 20, and 25 but no at INR 30, then their WTP is INR 25. Once the farmer says no, the enumerator asks the farmer to confirm their decision and reminds them that the auction can be done only once and the result would be binding. After the farmer has confirmed their response, the enumerator proceeds to draw a price. The enumerator draws a price coupon from an opaque box containing coupons in the set of possible prices [10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70].<sup>1</sup> If the price drawn is lower or equal to the individual's bid, they purchase the bag at the drawn price. If the price drawn is higher than the individual's bid, they do not qualify to purchase the bag. Continuing with the above example, if the price drawn was INR 20, farmer A, whose WTP was INR 25, qualifies to purchase the technology. However, a different farmer (say, farmer B) whose WTP was also INR 25 but whose random price draw was INR 30 will not qualify to buy the technology. Both farmers A and B have the same WTP, but based on a random price draw, farmer A is assigned to the treatment, and farmer B is assigned to the control group. We repeat this process for each individual participant in the sample.

By design, farmers who have a higher WTP are more likely to be assigned to the treatment group. In other words, the average treatment farmer has a higher WTP than the average control farmer. This would pose an identification issue if we tried to compare the outcomes of the average treatment and control farmers. However, note that our treatment is randomized at each level of WTP. Using our previous example,

<sup>1</sup> Fig. A2 in the Appendix shows the distribution of prices paid for the bags in the auction. The distribution of prices in the lottery is skewed to the left to increase the probability of farmers winning the auction and qualifying to purchase the bags.

both farmers A and B had the same revealed preference WTP of INR 25, but based on a random price draw, were assigned to treatment and control groups, respectively. Thus, farmers at each level of WTP are comparable. In other words, treatment is randomized conditional on each level of WTP. In our regression specification, this translates to using WTP fixed effects. Our experimental approach is similar to the selective trials approach in Chassang et al. (2012) and used in the field by Lybbert et al. (2018) and Magnan et al. (2015).

Once the auction concluded, the enumerators moved to the fourth and final step to help treatment farmers store the grains in their hermetic bags. Treatment farmers were asked for a preferred date and time to deliver the hermetic bags. Farmers were asked to have the payment ready at the time of delivery. At the farmer's preferred time, field enumerators delivered the hermetic bags and helped the farmer transfer their grain to the hermetic bags. While doing so, the enumerators also ensured that the grain to be stored in the hermetic bags was of similar quality compared to the rest of the farmer's grain. We did this to rule out any adaptive behavior where farmers might store better quality grains in hermetic storage bags. Once sealed, farmers were provided detailed instructions on the use and maintenance of the hermetic bags.

### 3.4. Experiment 2: Storage and sales experiment

To estimate economic losses and financial incentives for the adoption of technology, we need to understand if a price premium exists for better grain quality in the local markets. In our study area, each village had an average of two traders and 383 households. Traders may exercise higher market power that decreases both the price and the quality premium that farmers receive from improved grain quality. Therefore, we cannot assume that improved grain quality from better storage would translate into better prices for farmers. To estimate whether price premia for improved quality exists, we use a second field experiment to test whether farmers receive a higher price in the local market for grains stored in hermetically sealed bags. We take a sub-sample of 200 maize farmers across 35 villages for a storage and sales experiment conducted over a period of four months. The storage and sales experiment uses a within-farmer design wherein an individual farmer sells a bag of traditionally stored grain and a bag of hermetically stored grain on the same day to the same trader.

Each farmer in this experiment received two hermetic bags (free of cost) as an incentive to participate. The farmers were encouraged to store their maize harvest in these bags and two other traditional bags. Similar to the auction experiment, field enumerators ensured that farmers stored maize of the same quality in both types of bags. After storing the maize, farmers were asked to sell grain from one hermetic bag and one traditional bag on a particular date. The first sale was approximately two months after harvest, and the next sale was four months after harvest. Each farmer sold both the hermetically stored maize and the maize from the traditional bag separately to the same trader on the same day. The maize in the hermetic bag was taken out from the bag (since farmers did not want to sell the hermetic bag along with the maize and we did not want the appearance of the bag to influence traders' valuation), transferred to a usual traditional bag and then sold to the trader. Each bag was marked to ensure that the grain was not mixed for sale. Field staff accompanied each farmer to the trader and recorded the price for each batch of maize right after the sale. Enumerators were trained and instructed to act as non-participant observers to ensure that they did not influence the bargaining and price discovery process.

Traders who bought the grain were unaware that the grain had been stored in a hermetic bag. As a result, any difference in price between hermetic and traditionally stored grain must result from differences in the quality attributes as valued by the trader. Our within-farmer design ensures that the effect is not confounded by variation in market conditions, formal or informal contracts that a farmer has with a trader, or other factors. We interpret this difference as the price premia from

improved storage quality due to hermetic bags.

## 4. Data

### 4.1. Data collection, descriptive statistics, and attrition

**Experiment 1:** We reached out to a total of 2100 households (50 households  $\times$  42 villages) to participate in the auction experiment. Since we completed auctions in each village in one day to avoid strategic behavior among farmers, we could not contact the household heads of all the sampled households on the same day in each village. Out of 2100, we found 1511 household heads that we invited to participate in the auction. Of those, 66 farmers refused to participate on religious grounds.<sup>2</sup> The remaining 1445 households agreed to participate in the auction.

Before starting their auction, we informed each participant that the auction process would be binding: if they qualified, they would need to purchase the bags at the price that was drawn. All of those who won the auction paid for the bags and used the technology. Attrition between baseline and follow-up was minimal. Out of the 1445 participating households, 16 households (1.1 % of the sample) could not be covered in the follow-up survey.<sup>3</sup>

Our final estimation sample consists of 1429 farmers. The treated group comprised 814 farmers. These are farmers who qualified in the auction (for whom the price drawn ended up being lower than or equal to their WTP) and purchased the technology. The control group consists of 615 farmers who did not qualify – i.e., the price drawn for them was higher than their WTP – and did not get to purchase the hermetic bags. [Table A1](#) in the Appendix summarizes the baseline descriptive characteristics and balance between the treatment and control groups for the auction experiment sample. Overall, we find that conditional on WTP, treatment and control group farmers share similar characteristics.

**Experiment 2:** For the storage and sales experiment, 200 farmers were recruited initially. One farmer dropped out during the experiment before the first sale occurred. Our final sample consists of 199 farmers, each of whom undertook four maize sale transactions, resulting in 796 observations.

### 4.2. Timeline of experiments

**Experiment 1:** We began with a baseline survey in November 2015 before conducting the first round of field auctions in June 2016, two weeks before the maize harvest in our study area. Six months after farmers had stored grains, we tested grain samples from hermetic and traditional jute bags for aflatoxin contamination<sup>4</sup> and insect and fungal damage levels. After the farmers had the opportunity to use hermetic bags for two agricultural seasons, we conducted a follow-up survey with all treatment and control group participants in July 2017.

**Experiment 2:** From July to November 2018, we conducted the storage and sales experiment to measure the price premium available to farmers for better grain quality stored in hermetic bags. [Fig. A3](#) in the Appendix shows the timeline of interventions and data collection of our

<sup>2</sup> The 66 farmers who refused to participate were Muslims who perceived the auction as gambling or a game of chance which is strictly forbidden by Islamic law.

<sup>3</sup> We find no evidence of selective attrition. Regressing an indicator for attrition on the treatment dummy and WTP fixed effects results in a coefficient of 0.007 with a standard error of 0.006.

<sup>4</sup> We used the ELISA test to determine the level of aflatoxin in our samples. The US government enforces 20 ppb as the permissible limit of aflatoxin in food grains while the European Union uses a 10-ppb limit. The government of India prescribes an aflatoxin limit of 30 ppb for food grains, but we did not find any evidence of enforcement of this limit in any literature, news reports, or among farmers, grain traders, warehouse managers, retailers, and consumers.

experimental design.

## 5. Estimation strategy

### 5.1. Experiment 1: Estimation strategy for auction

We estimate the treatment effect in the auction experiment through the following equation:

$$Y_{i,v,d} = \beta_0 + \beta_1 T_i + \mu_{WTP} + \delta X_i + \lambda_{v,d} + \varepsilon_i \quad (1)$$

where  $Y_{i,v,d}$  is the outcome for farmer  $i$  in village  $v$  and district  $d$ . Treatment is denoted by  $T_i$ , an indicator taking the value 1 if the farmer purchased hermetic bags in the auction. As we discuss in our experiment design, the treatment is randomized conditional on WTP levels. To operationalize this design, our regression model includes a vector of WTP fixed effects ( $\mu_{WTP}$ ). The coefficient on treatment  $\beta_1$  measures the marginal effect at the extensive margin - i.e., the impact of moving from no hermetic bags to at least one hermetic bag.

In the results, we start by presenting the estimates of  $\beta_1$  when only the WTP fixed effects are included. We then progressively add more controls. Our preferred set of estimates include village fixed effects (FE), denoted by  $\lambda_v$ , and  $X_i$ , a vector of baseline covariates shown in Appendix Table A1. Under this specification, we compare the outcomes for farmers who qualified for hermetic bags to farmers who did not qualify within the same village and within each WTP level. While this is our preferred specification, we show results from alternate models that exclude control variables or use district instead of village fixed effects. Overall, our results remain robust across these alternate specifications. We cluster standard errors at the village level. Additionally, we also present Romano-Wolf stepdown adjusted p-values to correct for multiple hypotheses testing (Romano and Wolf, 2005).<sup>5</sup> All outcomes were measured using the follow-up survey and estimated on the full auction sample using the specification from Equation (1).

### 5.2. Robustness check

Our main estimation strategy compares farmers in the treatment and control groups at each level of WTP. To lend additional credibility to our results, we follow the approach by Berry et al. (2020), who use a similar BDM auction design followed by randomization to measure the impact of water filters in Northern Ghana.<sup>6</sup> Berry et al. (2020) use the random price drawn as an instrument for treatment assignment. We use the basic treatment equation (3):

$$Y_{i,v,d} = \beta_0 + \beta_1 T_i + \varepsilon_{i,v,d} \quad (3)$$

where  $Y_{i,v,d}$  is the outcome for farmer  $i$  in village  $v$  and district  $d$ . Treatment is denoted by  $T_i$ , an indicator taking the value 1 if the farmer purchased hermetic bags in the auction and  $\varepsilon_{i,v,d}$  captures unobservable determinants of  $Y$ . To instrument for the treatment variable, we estimate the first stage equation:

$$T_i = \gamma_0 + \gamma_1 P_i + \omega_i \quad (4)$$

where  $P_i$  is the random price drawn for the farmer  $i$ . The price drawn is a valid instrument because it strongly predicts treatment but is unconditionally exogenous and uncorrelated to the error term in equation (3). Table A2 in the Appendix shows the first-stage estimates. The price drawn is a strong predictor of treatment assignment. A reduction in the

<sup>5</sup> Romano-Wolf correction controls the familywise error rate and takes into account the dependence structure of the test statistics by resampling from the original data. We implement this using the `rwolf` package in Stata (Clarke et al., 2020) using a 1000 bootstrap repetitions. The outcome groups used in estimation are shown in Appendix Table A13.

<sup>6</sup> See Chassang et al. (2012) and Lybbert et al. (2018) for more discussion on experiment designs using an auction followed by randomization.

price of INR 5 increases the probability of treatment by 13.5 percentage points. We use 2SLS to estimate the IV coefficient on treatment. For comparability with our main OLS estimates, we include baseline controls and village fixed effects in the 2SLS specification as well. By design, the instrument is uncorrelated to farmer unobservables, including baseline willingness to pay. However, as a further check, we also show results from specifications including WTP fixed effects in addition to baseline controls and village fixed effects.

### 5.3. Experiment 2: Estimation strategy for storage and sales experiment

Our estimation strategy for the storage and sales experiment takes advantage of the within farmer design - each farmer in the sample sells one bag of hermetically stored and traditionally stored maize simultaneously and to the same trader. As a result, the farmer- and time of sale-specific difference in the price received for the hermetic and traditional storage reflects the effect of quality alone (driven by the storage type). Our design ensures that this effect is not confounded by variation in market conditions, formal or informal contracts that a farmer has with a trader, or other factors. We measure the impact of improved storage on market price premia using the following equation:

$$Y_{i,v,d,b} = \beta_0 + \beta_1 T_{i,b} + \delta X_{i,b} + \lambda_i \quad (2)$$

where  $Y_{i,v,d,b}$  is the outcome for farmer  $i$  in village  $v$  and district  $d$  for the maize stored in bag type  $b$ . The primary outcome variable is the sale price received by the farmer. The variable  $T_{i,b}$  is a binary  $\{0, 1\}$  variable taking the value 1 if the observation corresponds to maize stored in a hermetic bag and the value 0 if it is traditional bag storage. Exploiting the within-farmer design of the experiment, our specification also includes farmer-level fixed effects  $\lambda_i$ . Thus, the coefficient  $\beta_1$  captures the variation in outcomes for grain stored by the same farmer but in different storage types. The variable  $X_{i,b}$  is a vector of farmer-sale specific controls. These include storage duration and date of sale dummies to control for any variation in prices due to the timing of the sale. In qualitative surveys, traders report grain moisture as the chief quality characteristic that determines the prices they offer for maize. Therefore, we also control for grain moisture at the time of sale and the change in moisture from storage to sale. We also estimate the regression above using the percent change in grain moisture from storage to sale as the dependent variable to examine the effect of hermetic storage on preserving grain moisture levels. We drop the grain moisture at the sale from the control variables when estimating the effect on the change in grain moisture content.

## 6. Results

### 6.1. Experiment 1: Impact on grain damage, sales, consumption, aflatoxin, and storage duration and quantity

Our first set of results in Table 1 examines the impact of using hermetic bags on the physical availability of food by reducing postharvest grain losses due to rodent and pest damage. In Panel A of Table 1, using the auction experiment sample, we compare losses for grains stored in hermetic bags by treatment farmers to grains stored in traditional bags by control farmers at the same level of WTP. Note that by making a bag-level comparison, we measure the impact of storing grains in a hermetic bag versus a traditional bag. Column (4) of the table presents the estimates from our preferred specification. Our estimates show a 9-percentage point (pp) reduction in the likelihood of rodent damage and a 4 percentage point reduction in the likelihood of fungus or pest damage in hermetic bags. Relative to the control group mean, this translates to a nearly complete elimination in the likelihood of rodent and pest or fungal damage.

These bag-level storage loss outcome measures could be biased if farmers in the treatment group chose to store better quality grain in the

**Table 1**  
Impact on the likelihood of damage to grains due to rodents or pests.

	(1) No controls	(2) District FE	(3) District FE + controls	(4) Village FE + controls	(5) Control group mean	(6) Observations
Panel A: Treatment group, hermetic storage - Control group, traditional storage						
Rodent damage (Yes = 1)	-0.0797*** (0.0220)	-0.0769*** (0.0215)	-0.0765*** (0.0212)	-0.0844*** (0.0239) <i>[0.0099]</i>	0.0797	1429
Fungus/pest damage (Yes = 1)	-0.0362*** (0.0109)	-0.0360** (0.0110)	-0.0358** (0.0114)	-0.0368** (0.0121) <i>[0.0495]</i>	0.0374	1429
Panel B: Treatment group, traditional storage - Control group, traditional storage						
Rodent damage (Yes = 1)	0.00509 (0.0145)	0.0105 (0.0131)	0.00928 (0.0134)	-0.0127 (0.0126) <i>[0.3762]</i>	0.0797	1429
$H_0 : \beta \geq 10\%$ of control mean ( <i>p</i> -value)				0.041		
$H_0 : \beta \geq 50\%$ of control mean ( <i>p</i> -value)				4.108e-06		
Fungus/pest damage (Yes = 1)	0.0203 (0.0148)	0.0221 (0.0145)	0.0209 (0.0139)	0.0127 (0.0138) <i>[0.4257]</i>	0.0374	1429
$H_0 : \beta \geq 10\%$ of control mean ( <i>p</i> -value)				0.318		
$H_0 : \beta \geq 50\%$ of control mean ( <i>p</i> -value)				0.046		
Panel C: Farmer-level estimates of the likelihood of damage to grains						
Rodent damage at farmer-level (Yes = 1)	-0.0459*** (0.0153)	-0.0429*** (0.0142)	-0.0419*** (0.0141)	-0.0518*** (0.0153) <i>[0.0396]</i>	0.0797	1429
Fungus/pest damage at farmer-level (Yes = 1)	-0.0135 (0.0108)	-0.0149 (0.0103)	-0.0152 (0.0103)	-0.0176* (0.0107) <i>[0.1980]</i>	0.0374	1429

Notes: Each cell shows coefficient and SE on the treatment variable from a separate OLS regression estimated using Equation (1). Column (1) is OLS with only WTP fixed effects and no other controls. Column (2) adds district fixed effects (FE). Column (3) also adds baseline controls. Column (4) includes baseline controls, willingness to pay fixed effects, and village fixed effects. Panel A compares the outcomes for grain stored in hermetic bags by treatment group farmers with outcomes for grain stored in traditional bags by control group farmers. Panel B compares grain stored in traditional bags by treatment group farmers to grain stored in traditional bags by control group farmers. Panel B also shows results from one-sided non-inferiority significance tests (Walker and Nowacki, 2011) of whether the estimated treatment coefficient is no >10 % and no >50 % of the control group mean. Panel C compares aggregated outcomes at the farmer-level. For treatment group farmers, the outcome is the weighted mean of the outcome across hermetic and traditional storage, with the weights being the share of grain stored in each type of bag. Table A6 in the Appendix provides a full set of results with the controls for the preferred specification in Column (4). Standard errors in parentheses clustered at the village level. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$  based on conventional *p*-values. For the preferred specification in Column (4), Romano-Wolf stepdown *p*-values are shown in italics in square brackets.

hermetic bags. If this were the case, our estimates would reflect both the hermetic bag impact and the additional effect of pre-storage sorting. To curb such possible adaptive behavior, field enumerators ensured that farmers stored grains of similar quality in both hermetic and traditional bags. As an empirical test, we compare the incidence of grain damage in traditional storage bags among the treatment and control group farmers in Panel B of Table 1. We see no significant differences between treatment and control farmers. However, the coefficient on treatment is positive, albeit noisy, for fungus/pest damage. Using a one-sided non-inferiority test (Walker and Nowacki, 2011), we cannot reject that the difference between treatment and control groups for fungus/pest damage in traditional storage is >10 % of the control group's (*p*-value is 0.318). But our one-sided test suggests that the difference between treatment and control groups is no >50 % of the control mean (*p*-value is 0.046).<sup>7</sup>

To further investigate the extent to which our estimates may be biased due to pre-storage sorting, we estimate the impact on the likelihood of rodent and pest, or fungal damage aggregated at the individual farmer-level. Farmer-level outcomes for the treatment group are the weighted means of the likelihood of rodent or pest/fungal damage across hermetic and traditional bags, with the weights being the share of grain stored in each storage type. Estimating the impact on the

likelihood of grain damage at the farmer-level ensures that the treatment effect is not biased by potential pre-storage sorting. This approach is similar to the strategy used by Emerick et al. (2016).

The results of this analysis are presented in Panel C of Table 1. Using our preferred specification (column 4 of Panel C, Table 1), we find that access to at least one hermetic bag results in a 5.2 percentage point decrease in the likelihood of rodent damage at the farmer-level. For fungus or pest damage, the decrease is 1.8 percentage points, significant at the 10 percent level. Overall, the results in Panel C suggest that hermetic storage reduces the potential grain damage during storage, taking into account any pre-storage sorting. These results point towards the potential quantity gains that hermetic storage offers.

To understand the impact of improved storage on the market engagement of farmers, we look at the effect of treatment on the likelihood and frequency of grain sales in the market in Table 2. We find that the treatment group experienced a 30 percent increase in the likelihood of selling grains in the market compared to the control group. These results are similar to those of Aggarwal et al. (2018), who find that when farmers are given access to a program for communally storing maize, they are 37 percentage points more likely to sell maize and sell later at higher prices. We also see a small increase in the number of times farmers sold grain in the market, though the standard error is noisy in our preferred specification in Column (4) of Table 2.

Next, we compare how improved storage can impact affordable access to food by reducing the need to buy back from the market when prices are higher. We estimate potential substitution between market and own stocks as sources of household grain consumption. In Table 3, we see that even though the quantity of rice and wheat consumed does not change, the source of rice consumption from own stocks increases by 25 percent for the treated group compared to the control group.

<sup>7</sup> We also show results from a complementary bag-level analysis using an IV approach. The unit of observation in this analysis is an individual bag. We regress the damage outcomes on the type of storage bag (hermetic or traditional), instrumenting for storage type using the random price drawn in the auction. The estimates presented in Table A3 in the Appendix, and the results are similar to those shown in Panel A of Table 1.

**Table 2**  
Impact on likelihood and frequency of grain sales in the market.

	(1) No controls	(2) District FE	(3) District FE + controls	(4) Village FE + controls	(5) Control group mean	(6) Observations
Likelihood of selling grains in the market	0.0932** (0.0288)	0.0892** (0.0281)	0.0576** (0.0222)	0.0602** (0.0209) <i>[0.0693]</i>	0.197	1429
Number of times sold grains in the market	0.202*** (0.0593)	0.224*** (0.0588)	0.208** (0.0673)	0.0816 (0.0515) <i>[0.2475]</i>	1.273	357

*Notes:* Each cell shows coefficient and SE on the treatment variable from a separate OLS regression estimated using Equation (1). Estimates in the first row use the full auction sample. The sample in the second row consists only of those farmers who made at least one sale. Column (1) is OLS with only WTP fixed effects and no other controls. Column (2) adds district fixed effects (FE). Column (3) also adds baseline controls. Column (4) includes baseline controls, willingness to pay fixed effects, and village fixed effects. Standard errors in parentheses clustered at village level. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$  based on conventional p-values. For the preferred specification in Column (4), Romano-Wolf stepdown p-values are shown in *italics* in square brackets. Table A8 in the Appendix provides full set of results with the controls for the preferred specification in Column (4).

**Table 3**  
Impact on the source and quantity of staple cereal (rice and wheat) consumed.

	(1) No controls	(2) District FE	(3) District FE + controls	(4) Village FE + controls	(5) Control group mean	(6) Observations
Rice consumed (Days in the past week)	-0.0633 (0.0657)	-0.0258 (0.0558)	0.0174 (0.0557)	0.0335 (0.0307) <i>[0.3168]</i>	6.741	1429
Main source of rice consumption is own stocks = 1	0.112** (0.0359)	0.116*** (0.0329)	0.104** (0.0316)	0.0622** (0.0251) <i>[0.0297]</i>	0.246	1429
Rice share of consumption from market sources (%)	-9.366** (3.508)	-8.110** (3.373)	-6.829** (3.214)	-3.297 (2.532) <i>[0.5941]</i>	61.29	1429
Wheat consumed (Days in the past week)	0.0675 (0.0848)	0.111* (0.0649)	0.0982** (0.0479)	0.0491 (0.0411) <i>[0.2475]</i>	6.603	1429
Main source of wheat consumption is own stocks = 1	0.0970** (0.0362)	0.102** (0.0351)	0.0708** (0.0334)	0.0625** (0.0293) <i>[0.0891]</i>	0.382	1429
Wheat shares of consumption from market sources (%)	-8.966** (3.243)	-8.299** (3.147)	-5.700* (3.088)	-4.151* (2.254) <i>[0.2673]</i>	49.58	1429

*Notes:* Each cell shows coefficient and SE on the treatment variable from a separate OLS regression estimated using Equation (1). Column (1) is OLS with only WTP fixed effects and no other controls. Column (2) adds district fixed effects (FE). Column (3) also adds baseline controls. Column (4) includes baseline controls, willingness to pay fixed effects, and village fixed effects. Standard errors in parentheses clustered at village level. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$  based on conventional p-values. For the preferred specification in Column (4), Romano-Wolf stepdown p-values are shown in *italics* in square brackets. Table A9 in the Appendix provides full set of results with the controls for the preferred specification in Column (4).

Similarly, consumption from own stocks increases by 16 percent for wheat, and consumption from market sources decreases by 8 percent.<sup>8</sup> While we find some evidence of a shift away from market sources of grains to consumption from own stocks, we do not find an increase in the overall amount of rice or wheat consumed. This limited impact on overall consumption quantities of staples is similar to Basu and Wong (2015), who find that a seasonal food storage program and a food credit program had no impact on household staple food consumption. Their results and ours suggest that the average household may be close to staple food satiation. However, the substitution across sources of staples' consumption (from market to own) shows that such cost-saving behavior is an important component of the potential benefits of improved storage technology.

To study the utilization dimension of food security, we test the impact of improved storage on food safety, particularly aflatoxin contamination of grains. We collect grain samples from a sub-sample of

<sup>8</sup> Hoffmann and Gatabou (2014) argue that one of the reasons farmers value their own grain over market-purchased grain is the uncertainty about food safety attributes. This is different from our context because none of our sampled farmers, traders, or end-consumers knew about aflatoxins at baseline so, it is unlikely that they value their own grains more due to the belief that their grains have lower aflatoxin contamination.

treatment and control group farmers in the auction experiment to test for aflatoxin. In Table 4, we find that using hermetic bags decreases the incidence of aflatoxin by around 75 percent, the likelihood of aflatoxin contamination by 63 percent, and the likelihood of aflatoxin levels being above the safety threshold of 20  $\mu\text{g}/\text{kg}$  by 77 percent.

Improved storage eliminates the need to use toxic fumigants during storage. Farmers in our study area extensively use Aluminum Phosphide tablets (locally known as "Sulphas") during storage in traditional jute bags.<sup>9</sup> While training farmers for the proper use of hermetic bags, we stressed that grains stored in hermetic bags do not need Sulphas tablets. However, we know that several of our farmers did not follow this guideline – they continued to use the fumigant tablets despite there being no need for them. We were unable to monitor the use of these fumigant tablets and had to rely on self-reporting. Since we told farmers that they did not need to use fumigants, and some of them still did, we think that the self-reported measures of fumigant use are unreliable.

<sup>9</sup> Sulphas tablets are toxic if ingested with a mortality rate over 60% and have been reported as a common method of suicidal deaths in the region. Yet, they remain easily available over the counter. When Sulphas tablets come in contact with moisture in the air, they release Phosphine gas which in closed storage rooms is toxic when inhaled.

**Table 4**  
Impact of Improved Storage on Aflatoxin Incidence.

	(1) No controls	(2) District FE	(3) District FE + controls	(4) Village FE + controls	(5) Control group mean	(6) Observations
Aflatoxins ( $\mu\text{g}/\text{kg}$ )	-37.57*** (10.14)	-38.02*** (10.47)	-39.31*** (9.385)	-29.81*** (8.955)	40.16	197
1 if Aflatoxin > 0	-0.295*** (0.0645)	-0.283*** (0.0657)	-0.297*** (0.0537)	-0.275*** (0.0610)	0.436	197
1 if Aflatoxin > 20 $\mu\text{g}/\text{kg}$	-0.340*** (0.0632)	-0.340*** (0.0666)	-0.345*** (0.0552)	-0.304*** (0.0632)	0.393	197

Notes: Each cell shows coefficient and SE on the treatment variable from a separate OLS regression estimated using Equation (1). Column (1) is OLS with only WTP fixed effects and no other controls. Column (2) adds district fixed effects (FE). Column (3) also adds baseline controls. Column (4) includes baseline controls, willingness to pay fixed effects, and village fixed effects. Standard errors in parentheses clustered at village level. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$  based on conventional p-values. For the preferred specification in Column (4), Romano-Wolf stepdown p-values are shown in *italics* in square brackets. Table A10 in the Appendix provides full set of results with the controls for the preferred specification in Column (4).

While fewer treatment farmers self-reported the use of Sulphas tablets compared to control farmers, to be conservative, we do not use these estimates in our study.

Another important food security indicator that promotes the utilization of food to support a healthy life is dietary diversity. To understand the impact of improved storage on promoting a healthy diet, we look at non-staple cereal consumption and the dietary diversity of the auction experiment participants. We find no significant impact on any non-staple foods except an increase of 5 and 7 percent on sugar and dairy, respectively. As a result, we also find little impact on the dietary diversity score and food consumption value from all sources (see Tables A4 and A5 in Appendix for results on dietary diversity).

To study the impact of improved storage on inter-temporal consumption smoothing and, thus, the food security dimension of stability, we compare the probability, duration, and quantity of grain stored by

treatment and control farmers in the auction experiment. In Tables 5 and 6, we present results for the impact of access to improved storage on the likelihood of storage, storage duration, and share of output and quantity stored. Table 5 shows that farmers who had access to improved storage were 27, 29, and 30 percent more likely to store rice, maize, and any staple grain compared to the control group. The treatment group's storage duration was also significantly higher by approximately 24, 28, and 25 percent for rice, maize, and any staple grain, respectively. In Table 6, we see a significant increase in the share and quantity of output stored after harvest. Treatment group rice and maize farmers stored 19 and 25 percent higher shares of their grain harvest compared to control group farmers. The quantity of rice, maize, and any staple grain stored increases by 24, 73, and 24 percent, respectively.

**Table 5**  
Impact on the likelihood and duration of grain storage.

	(1) No controls	(2) District FE	(3) District FE + controls	(4) Village FE + controls	(5) Control group mean	(6) Observations
Stored rice (Yes = 1)	0.110** (0.0365)	0.114** (0.0354)	0.117*** (0.0337)	0.0875** (0.0288) <i>[0.0297]</i>	0.325	1429
Stored maize (Yes = 1)	0.0566** (0.0289)	0.0550** (0.0196)	0.0570** (0.0190)	0.0347** (0.0145) <i>[0.0225]</i>	0.120	1429
Stored any grain (Yes = 1)	0.133** (0.0420)	0.138*** (0.0400)	0.142*** (0.0389)	0.1134*** (0.0318) <i>[0.1188]</i>	0.380	1429
Max. rice storage duration (days)	34.38** (12.35)	33.59** (11.41)	30.81** (10.55)	21.9502** (8.834) <i>[0.0396]</i>	90.03	1429
Max. maize storage duration (days)	8.330 (6.094)	7.560* (4.433)	9.456** (4.544)	7.0043* (3.827) <i>[0.0693]</i>	24.93	1429
Max. storage duration of any grain (in days)	36.39** (13.05)	35.49** (11.80)	33.97** (11.16)	26.1631** (9.0267) <i>[0.1782]</i>	103.4	1429

Notes: Each cell shows coefficient and SE on the treatment variable from a separate OLS regression estimated using Equation (1). Column (1) is OLS with only WTP fixed effects and no other controls. Column (2) adds district fixed effects (FE). Column (3) also adds baseline controls. Column (4) includes baseline controls, willingness to pay fixed effects, and village fixed effects. Standard errors in parentheses clustered at village level. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$  based on conventional p-values. For the preferred specification in Column (4), Romano-Wolf stepdown p-values are shown in *italics* in square brackets. Table A11 in the Appendix provides full set of results with the controls for the preferred specification in Column (4).

**Table 6**  
Impact on the share of output and quantity of grains stored.

	(1) No controls	(2) District FE	(3) District FE + controls	(4) Village FE + controls	(5) Control group mean	(6) Observations
Share of rice output stored after harvest (%)	6.862** (3.017)	7.065** (2.992)	7.792** (2.749)	5.733** (2.474) <i>[0.0594]</i>	29.67	1429
Quantity of rice stored after harvest (kg)	170.8** (70.23)	160.7** (56.27)	135.4** (53.09)	55.89 (39.40) <i>[0.1683]</i>	231.6	1429
Share of maize output stored after harvest (%)	3.689 (2.631)	3.475** (1.701)	4.057** (1.753)	2.212* (1.340) <i>[0.1089]</i>	8.776	1429
Quantity of maize stored after harvest (kg)	19.52** (6.919)	19.98*** (5.801)	19.15** (6.225)	13.83** (6.231) <i>[0.0495]</i>	18.86	1429
Quantity of any grain stored after harvest (kg)	190.4** (75.61)	180.7** (59.68)	150.1** (56.06)	62.88 (42.91) <i>[0.1188]</i>	258.0	1429

Notes: Each cell shows coefficient and SE on the treatment variable from a separate OLS regression estimated using Equation (1). Column (1) is OLS with only WTP fixed effects and no other controls. Column (2) adds district fixed effects (FE). Column (3) also adds baseline controls. Column (4) includes baseline controls, willingness to pay fixed effects, and village fixed effects. Standard errors in parentheses clustered at village level. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$  based on conventional p-values. For the preferred specification in Column (4), Romano-Wolf stepdown p-values are shown in *italics* in square brackets. Table A12 in the Appendix provides full set of results with the controls for the preferred specification in Column (4).

## 6.2. Robustness check: IV estimates

The results presented above for the auction experiment rely on the OLS specification from equation (1). As a robustness check, we re-estimate the treatment effect using the price drawn in the BDM as an instrument for treatment assignment. We have a strong first-stage, evidenced by a Kleibergen-Paap F-statistic of 3127, well above the acceptable threshold for a strong instrument. Table 7 presents the linear two-stage least squares (2SLS) estimates for the coefficient on treatment. To facilitate comparison, column (1) of the table replicates the treatment coefficients from the preferred OLS specification. The corresponding IV-2SLS estimates are shown in column (2). In column (3), we present the estimates from including WTP fixed effects in the IV model. Overall, we see that the IV estimates remain very similar to the OLS estimates presented earlier.

## 6.3. Experiment 2: Impact on market price

Using the storage and sales experiment, we measure whether the quality gains from using improved storage translate to improved market returns for farmers. The average prices received for maize stored over the four months in hermetic and traditional bags were INR 1218 and INR 1115 per quintal, respectively. Table 8 presents the estimates for the regression in equation (2). Table 8 shows the estimates without any fixed effects and then with fixed effects at the district or village level, along with the control variables in columns (1), (2), and (3), respectively. Column (4) presents our preferred specification using farmer-level fixed effects. Our estimates indicate that the maize from hermetic bags received, on average, 13 percent higher prices than that stored in traditional bags. These regression results confirm that hermetic bags not only preserve grain quality but these quality attributes also translate into better market prices for the farmers in their local markets. Table 8 also shows the effect of hermetic storage on preserving grain moisture

through the duration of storage. We measured the moisture level since local traders reported grain moisture as a key indicator of maize quality and a strong determinant of its market price. We find that while maize stored in traditional jute bags experiences an average change in grain moisture of nearly 8 percent, grain moisture within the hermetic bags remains essentially unchanged. The change in moisture levels during traditional storage is likely to be associated with the worsening of other grain quality attributes, leading to a lower price in the market.

Table 9 summarizes our results on all the outcome variables we measure for each dimension of food security. Apart from dietary diversity, we find that improved storage positively impacts all food security indicators for treatment households.

## 7. Cost-benefit analysis of improved storage technology

We sum up the various benefits of improved storage on all dimensions of food security to conduct a cost-benefit analysis of improved storage technology. We calculate the monetary value of reducing physical grain losses due to rodent and fungal damage, higher prices received from selling in the market after two months, or cost-saved due to substitution away from market sources to own stocks for home consumption. We also consider the potential for farmers to sell grains to higher-value markets due to the reduction in aflatoxin contamination. A focus group discussion with maize traders in high-value markets in Hyderabad and Delhi informed us that one of the reasons these traders do not buy maize from Bihar is the high levels of aflatoxin in maize. Since reduced aflatoxin contamination is one of the benefits of improved storage, we consider the possibility that access to improved storage may offer farmers the opportunity to sell their grains in higher-value markets. However, other market failures, such as a lack of information and aflatoxin testing infrastructure, may prove to be a barrier to accessing higher-value markets. Therefore, we also consider the scenario in which the market premium for aflatoxin-free grains is unavailable. Each

Table 7

Treatment effect on outcome measures: IV estimates.

Outcome	(1) OLS	(2) IV (2SLS)	(3) IV (2SLS)
Incidence of grain damage in traditional storage bags by both treatment and control groups:			
Rodent damage = 1	-0.012 (0.012)	-0.025 (0.016)	-0.024 (0.016)
Fungus/pest damage = 1	0.012 (0.014)	0.000 (0.014)	0.001 (0.014)
Incidence of damages for grain stored in hermetic bags by treatment group versus grain stored in traditional bags by control group:			
Rodent damage = 1	-0.078*** (0.020)	-0.078*** (0.013)	-0.077*** (0.013)
Fungus/pest damage = 1	-0.037*** (0.012)	-0.046*** (0.011)	-0.045*** (0.011)
Farmer-level incidence of grain damage:			
Rodent damage = 1	-0.052*** (0.015)	-0.056*** (0.013)	-0.056*** (0.013)
Fungus/pest damage = 1	-0.018* (0.011)	-0.028** (0.011)	-0.026** (0.011)
Likelihood of selling grains in the market	0.060*** (0.021)	0.073*** (0.024)	0.070*** (0.024)
No. of sales	0.074 (0.047)	0.062 (0.069)	0.049 (0.072)
Rice consumed (days in the past week)	0.033 (0.030)	0.072* (0.039)	0.070* (0.039)
Main source of rice consumption is own stocks	0.062** (0.025)	0.055** (0.025)	0.057** (0.025)
Rice share of consumption from market sources (%)	-3.287 (2.487)	-2.989 (2.573)	-2.929 (2.542)
Wheat consumed (days in the past week)	0.049 (0.040)	0.050 (0.040)	0.047 (0.040)
Main source of wheat consumption is own stocks	0.063** (0.029)	0.074*** (0.027)	0.073*** (0.027)
Wheat share of consumption from market sources (%)	-4.153* (2.210)	-5.231** (2.449)	-5.137** (2.443)
Aflatoxin incidence:			
Aflatoxins (µg/kg)	-28.628*** (9.351)	-185.001* (109.905)	-184.334* (106.171)
Aflatoxin present = 1	-0.279*** (0.066)	-0.709* (0.426)	-0.657 (0.442)
Aflatoxin > 20 µg/kg)	-0.294*** (0.065)	-0.832** (0.421)	-0.770* (0.436)
Stored rice (Yes = 1)	0.088*** (0.028)	0.073*** (0.025)	0.078*** (0.025)
Stored maize (Yes = 1)	0.035** (0.014)	0.034* (0.020)	0.035* (0.019)
Stored any grain (Yes = 1)	0.113*** (0.031)	0.111*** (0.025)	0.114*** (0.025)
Max. rice storage duration (days)	22.033** (8.717)	22.742*** (7.553)	23.530*** (7.525)
Max. maize storage duration (days)	7.084* (3.790)	8.002* (4.416)	8.138* (4.352)
Max. storage duration of any grain (in days)	26.298*** (8.925)	28.909*** (7.489)	29.373*** (7.449)
Share of rice output stored after harvest (%)	5.763** (2.444)	4.979** (2.302)	5.532** (2.268)
Quantity of rice stored after harvest (kg)	56.109 (38.660)	38.691 (27.142)	42.720 (27.149)
Share of maize output stored after harvest (%)	2.253* (1.331)	1.418 (1.546)	1.583 (1.527)
Quantity of maize stored after harvest (kg)	13.977** (6.264)	12.951* (7.735)	12.876* (7.628)
Quantity of any grain stored after harvest (kg)	63.351 (42.103)	37.399 (32.184)	40.887 (32.346)

Notes: Each cell shows the coefficient on treatment (purchased hermetic bags) corresponding to the outcome shown in the first column. The sample consists of 1429 farmers who participated in the BDM auction (Experiment 1). Column (1) "OLS" shows the estimates from the main OLS specification from equation (1) which includes WTP fixed effects, village fixed effects, and baseline controls. Columns (2) and (3) show the 2SLS estimates from equations (3) and (4) using BDM price drawn as an instrument for treatment. Column (2) includes controls for village fixed effects and baseline controls. Column (3) additionally controls for WTP fixed effects. The 1st stage Kleibergen-Paap F-statistic is 3126.53. For the aflatoxin sample, the 1st stage F-stat is much lower (18.89) due to the smaller sample size. Standard errors in parentheses are clustered at the village level. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

**Table 8**  
Impact of storage type on market price and change in grain moisture for maize.

	(1) No FE	(2) District FE	(3) Village FE	(4) Farmer FE	(5) Mean (traditional bag)	(6) Observations
Sale price (INR/quintal)	148.5*** (15.79)	152.7*** (14.38)	151.2*** (10.36)	152.6*** (10.78)	1115.3	796
% Change in grain moisture	-7.338*** (0.361)	-7.338*** (0.359)	-7.338*** (0.347)	-7.338*** (0.352)	7.838	796

Note: Each cell shows the coefficient and SE on the hermetic bag storage variable from separate regressions estimated using Equation (2). Column (1) is OLS without any fixed effects. Column (2) includes district fixed effects (FE) and controls. Column (3) is similar to village-level FE. Column (4) uses farmer-level FE. Control variables include the date of sale dummies and duration of storage. Additionally, the sale price regressions also include grain moisture level at the time of sale and change in moisture level from storage to sale. Standard errors in parentheses clustered at the farmer level. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ . Table A7 in the Appendix provides the full set of results with the controls for the preferred specification in Column (4).

**Table 9**  
Impact of Improved Storage on all dimensions of Food Security.

Food Security Indicator	Variables Measured	Results <i>Improved Storage...</i>
Availability	Physical grain losses due to rodent, pest, or fungal damage	Reduced physical losses by nearly 100 %
Access	Price received for stored grains	Increased price received by 13 %
	Change in market engagement	Increased likelihood of selling stored grains in the market by 30 %
Utilization	Consumption from and substitution between market vs. own stock	Increased consumption from own stocks by 20 %; decreased from market sources by 8 %
	Aflatoxin contamination	Reduced aflatoxin contamination by 75 %
Stability	Dietary diversity	No change in dietary diversity
	Likelihood and duration of storage	Increased the duration of storage by 25 %
	Share of grain stored for later consumption	Increased the share of grain stored by 20 %

hermetic bag has a capacity of 50 kgs (110 lb.) and was available at the unsubsidized retail price of INR 80 (~USD 1.20) per bag during the time of the intervention (2016–2018).

Our cost-benefit analysis demonstrates a high return to the use of improved storage technology relative to the typical storage methods farmers currently use. We assume two potential scenarios – one, where all the grain stored is sold in the market, and the other, where all the grain stored is used for own consumption. We calculate the financial benefits, and while we do not monetize the health benefits, we comment on the health impacts of consuming aflatoxin-contaminated grain using previous studies on the health benefits of improved storage technology. Our analysis also takes into account that hermetic bags are reusable. At the time of the follow-up survey, over 95 % of the treatment farmers in our sample were reusing the bags for a fourth season.

### 7.1. Financial benefits

Table 10 presents the cost-benefit analysis of improved storage under two scenarios, including estimates with and without the premium from selling aflatoxin-free grains in high-value markets. We use the following data and assumptions for our cost-benefit calculations.

1. Quantity calculation (row a) - Our experiment on physical loss measurement shows that an average of 10 percent of grain is lost to pest, fungal, and rodent damage in traditional storage. We also find that nearly 100 percent of this damage is eliminated by using improved storage. Thus, the quantity available for consumption or sale is 45 kg from traditional bags and 50 kg from improved storage.

- Value calculation (row b) - Maize stored for an average of two months after harvest in traditional storage fetched INR 1085 per quintal (or INR 10.85 per kg), while that stored in improved storage fetched INR 1202 per quintal (or INR 12.02 per kg) – an increase of 10.8 percent in price. We also know that the average price of medium-quality grain purchased from local traders/retailers is INR 22 per kg.
- Cost of bag calculation (row d) - The cost of a jute bag is INR 10, and the cost of the hermetic storage bags used for this experiment is INR 80 per bag. Our follow-up survey found that the improved storage bags were being reused by nearly all farmers for four seasons. To take this into account, we spread the cost of storage technology over four agricultural seasons (or two years). However, improved (hermetic) storage bags are best used as an additional inner layer with traditional bags to ensure longevity and effectiveness. Therefore, we add the cost of traditional bags to hermetic bags to calculate the total cost of using improved storage (i.e., the cost of improved storage per season:  $[(80/4) + 10 = \text{INR } 30]$ ).
- Value calculation with potential aflatoxin-free premium (row g) – Traders surveyed in high-value markets (Hyderabad and Delhi) buy maize with low aflatoxin content at an average of INR 1300 per quintal (or INR 13 per kg). These traders reported not buying grains from Bihar due to high aflatoxin levels, particularly in maize. Improved storage reduces aflatoxin contamination by nearly 75 percent, bringing it down to permissible levels and providing farmers with opportunities to access high-value markets. Suppose we assume that nearly 50 percent of the difference in maize price is attributable to factors like transaction costs and non-aflatoxin-related unobservable grain quality. In that case, there is still a price premium for low aflatoxin grains for farmers  $(\text{INR } ((13 - 12.02) * 0.5) = \text{INR } 0.49)$ . Thus, the price per kg with the potential aflatoxin-free premium will be  $\text{INR } (12.02 + 0.49) = \text{INR } 12.51$ .

Whether all the grain stored is used for own consumption or sold in the market, we find that improved storage is profitable under both scenarios – with and without an aflatoxin-free premium. The benefit of using improved storage is highest when farmers can access high-value markets due to the reduction in aflatoxin levels. Fig. A4 in the Appendix plots the financial benefits, along with the cost of improved storage, under both scenarios to show the profitability of on-farm hermetic storage.

If we ignore the quality and economic losses and focus only on the physical quantity of grain saved by improved storage, the estimated additional benefit of using improved storage would be INR 34.50 (last column in Table 10). This estimate fails to capture nearly 60 to 70 % of the benefits from improved storage that come from reducing quality and economic losses.

**Table 10**  
Cost-Benefit Analysis of Improved Storage Technology.

For 50 kgs (110 lb.) stored in one bag for two months	Traditional Storage		Improved Storage		
	If all sold	If all consumed	If all sold	If all consumed	If only measuring quantity gains (for sale)
a. Consumable or saleable quantity	45 kg	45 kg	50 kg	50 kg	50 kg
b. Value per kg (from local traders)	INR 10.85	INR 22	INR 12.02	INR 22	INR 10.85
c. Total value (a * b)	INR 488.25	INR 990	INR 601	INR 1100	INR 542.50
d. Cost of storage bags	INR 10	INR 10	INR 30	INR 30	INR 30
e. Revenue – Cost	INR 478.25	INR 980	INR 571	INR 1070	INR 512.50
f. Additional benefit from using improved storage (for one season)	–	–	INR 92.75	INR 90	INR 34.25
<i>Including potential aflatoxin control premium</i>					
g. Value per kg	INR 10.85	INR 22	INR 12.51	INR 22	INR 10.85
h. Total value (a * g)	INR 488.25	INR 990	INR 625.50	INR 1100	INR 542.50
i. Revenue – Cost	INR 478.25	INR 980	INR 595.50	INR 1070	INR 512.50
j. Additional benefit from using improved storage	–	–	INR 117.25	INR 90	INR 34.25

## 7.2. Health benefits

Liu et al. (2012) estimate that nearly 21–24 % of hepatocellular carcinoma (HCC) cases globally can be attributed to aflatoxin contamination. Even though the health impacts of consuming aflatoxin-contaminated grains are not limited to HCC but include other serious health conditions like fetal malformation and neural congenital disabilities, among others (IARC, 2012), studies using HCC data find that aflatoxin reduction strategies can be very cost-effective (for example, Hoffmann and Jones, 2021). Wu and Khlangwiset (2010) estimate the economic health impact and cost-effectiveness of aflatoxin reduction strategies in Nigeria and Guinea using data on aflatoxin-induced HCC cases. They find that economic health benefits from aflatoxin reduction interventions in terms of lives saved and quality of life gained by reducing aflatoxin-induced HCC far exceed the cost of the intervention. The study estimates that the cost-effectiveness ratio (CER) of such interventions is greater than one, which is considered “very cost-effective” by the World Health Organization.

## 8. Conclusion

Reducing food losses is a promising way to increase the amount of food available for consumption, particularly in food-insecure regions of the world. While experimental evidence shows various technologies are effective at reducing postharvest losses, they remain mostly unadopted and unsupported by large-scale public policies. One reason for the lack of policy support to promote loss-reduction technologies may be the lack of evidence on returns to adoption.

We take the case of one such loss-reduction technology – improved storage – in the context of smallholder Indian farmers. We try to answer questions related to the economics of reducing food losses: What is the overall economic benefit of improved storage when accounting for quantity, quality, and income losses? Are these benefits economically significant for smallholder farmers in a developing country? Crucially, do the local markets offer economic incentives for adopting a loss-reduction technology in terms of positive returns to adoption?

We find that preventing food losses has significant economic benefits for smallholder farmers owing to quality, quantity, and income gains. Food losses prevent farmers from receiving better market prices for grains, benefiting from arbitrage, and storing for their own consumption to save costs on later purchases from more expensive market sources. We present experimental evidence that loss-reduction technologies like improved storage can alleviate many of these losses. Our estimates show that local rural markets, even in poorer states in India, offer economic incentives for preserving grain quality. Consequently, the benefits of adopting loss-reduction technologies like improved storage far outweigh its costs in our context. We find that farmers recover the full unsubsidized cost of the (reusable) improved storage technology in one agricultural season. Our cost-benefit analysis is one of the first in this

literature to estimate returns from the adoption of improved storage technology.

We find that, in addition to reducing physical grain losses, loss-reduction technologies can offer significant benefits on multiple dimensions of food security. Consequently, research on loss-reduction technology that focuses only on evaluating the gain in quantity fails to measure 60–70 % of the benefits of technology.

Understanding the economics of reducing food losses still needs more research in different contextual settings. We recognize that there is significant variation in where and how food losses occur, and a limitation of our study is that our results might not generalize to other loss-reduction technologies in other contexts. While there is similar research conducted in Africa and Latin America, ours is the only experimental evidence of the impact of improved storage in Asia and is not representative of the region.

## 9. Policy implications

For policymakers, our findings suggest that in areas where public and private storage infrastructure is scarce, cost-effective technologies like improved storage can act as a short- or medium-term measure to reduce postharvest losses. While initial subsidies may be required to promote adoption, in our associated work in the same study area, we find that farmers increase their willingness to pay for the technology after gaining experience using it for a year (Shukla et al., 2022; also see Channa et al., 2019 for a discussion on determinants of willingness to pay for improved storage).

While the losses in our context are economically significant, it is important to understand economic incentives in the supply chain before promoting the adoption of any loss-reduction technology. Whether financial and economic incentives exist in the market will vary with context, and returns to adoption will be an important determinant of the adoption of loss-reduction technology.

Given the large benefits of improved storage on food security, including food safety, improved storage technology may be particularly suitable for certain areas. Our findings suggest that improved storage can offer large gains for regions where farmers experience high storage losses, aflatoxin incidence, and possible price premia in the supply chain for grain quality.

## CRedit authorship contribution statement

**Pallavi Shukla:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Project administration. **Hemant K. Pullabhotla:** Conceptualization, Methodology, Data curation, Software, Validation, Formal analysis, Writing – review & editing. **Kathy Baylis:** Conceptualization, Supervision, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgment

The authors would like to thank the ADM Institute for the Prevention of Postharvest Loss at the University of Illinois for project funding support.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foodpol.2023.102442>.

## References

- Abass, A.B., Fischler, M., Schneider, K., Daudi, S., Gaspar, A., Rüst, J., Kabula, E., Ndunguru, G., Madulu, D., Msola, D., 2018. On-farm comparison of different postharvest storage technologies in a maize farming system of Tanzania Central Corridor. *J. Stored Prod. Res.* 77, 55–65.
- Affognon, H., Mutungi, C., Sanginga, P., Borgemeister, C., 2015. Unpacking postharvest losses in sub-Saharan Africa: a meta-analysis. *World Dev.* 66, 49–68.
- Aggarwal, S., Francis, E., Robinson, J., 2018. Grain today, gain tomorrow: evidence from a storage experiment with savings clubs in Kenya. *J. Dev. Econ.* 134, 1–15.
- Anriquez, G., Foster, W., Ortega, J., Rocha, J.S., 2021. In search of economically significant food losses: evidence from Tunisia and Egypt. *Food Policy* 98, 101912.
- Basu, K., Wong, M., 2015. Evaluating seasonal food storage and credit programs in east Indonesia. *J. Dev. Econ.* 115, 200–216.
- Bauchet, J., Prieto, S., Ricker-Gilbert, J., 2021. Improved drying and storage practices that reduce aflatoxins in stored maize: experimental evidence from smallholders in Senegal. *Am. J. Agric. Econ.* 103 (1), 296–316.
- Berry, J., Fischer, G., Guiteras, R., 2020. Eliciting and utilizing willingness to pay: evidence from field trials in Northern Ghana. *J. Polit. Econ.* 128 (4), 1436–1473.
- Bokusheva, R., Finger, R., Fischler, M., Berlin, R., Marín, Y., Pérez, F., Paiz, F., 2012. Factors determining the adoption and impact of a postharvest storage technology. *Food Secur.* 4 (2), 279–293.
- Brander, M., Bernauer, T., 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.
- Cattaneo, A., Sánchez, M.V., Torero, M., Vos, R., 2021. Reducing food loss and waste: five challenges for policy and research. *Food Policy* 98, 101974.
- Channa, H., Chen, A.Z., Pina, P., Ricker-Gilbert, J., Stein, D., 2019. What drives smallholder farmers' willingness to pay for a new farm technology? Evidence from an experimental auction in Kenya. *Food Policy* 85, 64–71.
- Chassang, S., Miquel, P.L., Snowberg, E., 2012. Selective trials: a principal-agent approach to randomized controlled experiments. *Am. Econ. Rev.* 102 (4), 1279–1309.
- Chegere, M.J., 2018. Post-harvest losses reduction by small-scale maize farmers: the role of handling practices. *Food Policy* 77, 103–115.
- Clarke, D., Romano, J.P., Wolf, M., 2020. The Romano-Wolf multiple-hypothesis correction in Stata. *Stata J.* 20 (4), 812–843.
- 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. *J. Stored Prod. Res.* 53, 27–36.
- Delgado, L., Schuster, M., Torero, M., 2021. Quantity and quality food losses across the value Chain: a Comparative analysis. *Food Policy* 98, 101958.
- Emerick, K., De Janvry, A., Sadoulet, E., Dar, M.H., 2016. Technological innovations, downside risk, and the modernization of agriculture. *Am. Econ. Rev.* 106 (6), 1537–1561.
- FAO, 2019. The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction. Rome, Italy.
- Food and Agriculture Organization, 1996. Rome Declaration on World Food Security and World Food Summit Plan of Action: World Food Summit 13-17 November 1996, Rome, Italy. FAO.
- Gitonga, Z.M., De Groote, H., Kassie, M., 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.
- Hoffmann, V., Jones, K., 2021. Improving food safety on the farm: experimental evidence from Kenya on incentives and subsidies for technology adoption. *World Dev.* 143, 105406.
- International Agency for Research on Cancer, 2012. Aflatoxins, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 100F. World Health Organization, Lyon, France.
- Leavens, L., Bauchet, J., Ricker-Gilbert, J., 2021. After the project is over: measuring longer-term impacts of a food safety intervention in Senegal. *World Dev.* 141, 105414.
- Liu, Y., Chang, C.C.H., Marsh, G.M., Wu, F., 2012. Population attributable risk of aflatoxin-related liver cancer: systematic review and meta-analysis. *Eur. J. Cancer* 48 (14), 2125–2136.
- Lybbert, T.J., Magnan, N., Spielman, D.J., Bhargava, A.K., Gulati, K., 2018. Targeting technology to increase smallholder profits and conserve resources: experimental provision of laser land-leveling services to Indian farmers. *Econ. Dev. Cult. Chang.* 66 (2), 265–306.
- Magnan, N., Spielman, D.J., Lybbert, T.J., Gulati, K., 2015. Leveling with friends: social networks and Indian farmers' demand for a technology with heterogeneous benefits. *J. Dev. Econ.* 116, 223–251. <https://doi.org/10.1016/j.jdeveco.2015.05.003>.
- Magnan, N., Hoffmann, V., Opoku, N., Garrido, G.G., Kanyam, D.A., 2021. Information, technology, and market rewards: incentivizing aflatoxin control in Ghana. *J. Dev. Econ.* 151, 102620.
- 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. *J. Stored Prod. Res.* 69, 119–128.
- Omotilewa, O.J., Ricker-Gilbert, J., Ainembabazi, J.H., Shively, G.E., 2018. Does improved storage technology promote modern input use and food security? Evidence from a randomized trial in Uganda. *J. Dev. Econ.* 135, 176–198.
- Pretari, A., Hoffmann, V., Tian, L., 2019. Post-harvest practices for aflatoxin control: evidence from Kenya. *J. Stored Prod. Res.* 82, 31–39.
- Reserve Bank of India, 2013. Handbook of Statistics on Indian Economy. RBI, New Delhi, India. <https://www.rbi.org.in/scripts/PublicationsView.aspx?id=15283>.
- Romano, J.P., Wolf, M., 2005. Exact and approximate stepdown methods for multiple hypothesis testing. *J. Am. Stat. Assoc.* 100 (469), 94–108.
- Sheahan, M., Barrett, C.B., 2017. Food loss and waste in Sub-Saharan Africa. *Food Policy* 70, 1–12.
- Shukla, P., Pullabhotla, H.K., Baylis, K., 2022. Trouble with zero: the limits of subsidizing technology adoption. *J. Dev. Econ.*, 102920.
- Somavat, P., Huang, H., Kumar, S., Garg, M.K., Danao, M.G.C., Singh, V., Paulsen, M.R., Rausch, K.D., 2017. Comparison of hermetic storage of wheat with traditional storage methods in India. *Appl. Eng. Agric.* 33 (1), 121.
- Stathers, T., Holcroft, D., Kitinoja, L., Mvumi, B.M., English, A., Omotilewa, O., Torero, M., 2020. A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asia. *Nat. Sustainability* 3 (10), 821–835.
- Tesfaye, W., Tirivayi, N., 2018. The impacts of postharvest storage innovations on food security and welfare in Ethiopia. *Food Policy* 75, 52–67.
- Walker, E., Nowacki, A.S., 2011. Understanding equivalence and noninferiority testing. *J. Gen. Intern. Med.* 26 (2), 192–196. <https://doi.org/10.1007/S11606-010-1513-8/TABLES/2>.
- Williams, S.B., Baributsa, D., Woloshuk, C., 2014. Assessing Purdue Improved Crop Storage (PICS) bags to mitigate fungal growth and aflatoxin contamination. *J. Stored Prod. Res.* 59, 190–196.
- Wu, F., Khlanguiswet, P., 2010. Health economic impacts and cost-effectiveness of aflatoxin-reduction strategies in Africa: case studies in biocontrol and post-harvest interventions. *Food Addit. Contam.* 27 (4), 496–509.