RESEARCH

The cost of inadequate postharvest management of pulse grain: Farmer losses due to handling and storage practices in Uganda

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Abstract

Background Investing in postharvest technologies is one way of reducing food losses with the aim of achieving food security, but it is often overlooked. In this study, we assessed the losses and costs associated with the harvest and postharvest practices used by smallholder bean farmers in Uganda. We also estimated the grain Moisture Content (MC) associated with traditional storage practices.

Results Harvest and postharvest handling practices result in a loss of about 22% of the crop harvest. The cost associated with this loss is 17% of the output value. In addition, the common storage practices used by farmers are unable to maintain the required grain MC of $\leq 13\%$. As even a slight change in grain MC can significantly impact storage duration, we found that 74% of farmers fail to meet the required MC, resulting in a loss of anticipated price premiums over an average storage duration of 80 days. Our econometric estimates suggest that storing grain in bags placed above the floor surface could reduce MC by an additional 1.5%.

Conclusions Our predictions indicate that farmers who use traditional practices should store bean grains for less than 60 days, or they should adopt better storage practices to increase shelf life and ensure food safety. If more farmers had placed their grain above the floor surface, 48% rather than 26% would have met the required MC at 90 days. It is worth noting that poor postharvest handling has significant economic implications and can lead to food safety concerns due to quality failures in the grain. To address these issues, there is a need to scale up interventions that increase farmer access to postharvest technologies.

Keywords Postharvest losses, Dry bean, Moisture content, Grain storage

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Background

Meeting sustainable future food demands will require both increasing food production and reducing food loss and waste [1–5]. Therefore, the global sustainable development goals (SDGs) prioritize global food security, with the aim of halving global food losses along supply chains and reducing food waste at the retail and consumer levels by 2030. Addressing leakages in food systems, including postharvest losses, is recognized as one of the pathways to achieving food security [2–4, 6–9]. Food losses occur at different stages of the food supply chain, ranging

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from harvesting, through primary processing, storage, and marketing, to final delivery to consumers [3, 9, 10]. Reducing food losses translates to an increase in the quantity of available food, thereby reducing food insecurity [3, 11]. This, in turn, reduces the need to supplement food access through policies that focus on transfer programs at the household level or commercial imports and food aid at the national level [12].

To achieve food security through policy efforts, it is crucial to have a comprehensive understanding of food issues across three dimensions: first, it is essential to identify the amount of food that is lost and wasted, as well as the reasons and locations for such loss and waste. Second, it is imperative to clarify the underlying objectives for reducing food loss and waste, which may be related to food security or environmental concerns; and third, it is crucial to understand how food loss and waste, as well as the measures to reduce them, impact the objectives being pursued [13, 14]. This study focuses the first dimension by investigating farmer-level losses in pulse production, particularly dry beans, which are essential to the food security of millions of households in developing countries.

Smallholder production and food losses in Africa

Agricultural production in developing countries is characterised by low productivity due to several factors such as low investments and adoption of improved technologies, and emerging challenges like climate change. These factors undermine total production and the ability of Africa to secure the food needs of its population [15]. For instance, bean yield in Uganda has been consistently low, ranging from 800 to 1200 kg per hectare, far below the potential farmer yield of 2000 kg per hectare. The low production is worsened by poor harvest and postharvest practices that further depresses total production [16]. Inappropriate practices such as poor storage contribute to postharvest food losses. The persistent food handling losses partly explains the food scarcity induced food insecurity that is common in developing countries [17]. Consequently, despite over 60% of the population being involved in agricultural production for livelihood, millions of food-insecure households around the world are in such developing countries [18]. Resolving food insecurity requires a more in-depth understanding of the nuances in food loss and the food system.

The annual cost of food loss and waste is significant, estimated at United States Dollars (USD) 680 billion in industrialised countries and USD 310 billion in developing countries [14]. In sub Saharan Africa (SSA), the World Bank [15] estimates that postharvest handling alone accounts for about USD 4 billion worth of food losses. This is approximately one-third of total food losses

in the region [19]. Interventions in postharvest handling can reduce postharvest losses, enhance food and nutrition security, and improve food safety [20]. For instance, reducing postharvest handling losses (PHL) in the form of food quality can improve food utilization among consumers [12].

Delayed adoption of postharvest handling technologies serves to perpetuate significant grain losses and compromises efforts on food security in Africa. The African Union (AU) has been part of the global food policy agenda, and in response to the Global Agenda 2030 and the AU Agenda 2063, the African Union strategies [21] for food security through the reduction of PHL were put in place, with initiatives being undertaken by various countries with support from several donors. As the Malabo commitment nears its end in 2025, information on commodity specific PHL reduction is essential for policy and investment efforts going forward. During the Nairobi AU coreference [22], a call was made to support AU member states in putting in place systems and processes to achieve the postharvest loss reduction target set in the Malabo Declaration. AU offered support to initiatives on PHL reduction in some countries and Uganda has benefited through the National Agricultural Research Organization (NARO) under the legumes programme.

Postharvest handling of dry bean in Uganda

Uganda is a major producer of dry beans in Africa, with over 70% of households involved in its production. While the government and development partners have invested in breeding and seed distribution to improve productivity, there has been less emphasis on developing postharvest technologies suited for bean handling. As a result, few farmers have access to proper storage facilities and information on appropriate postharvest handling practices and technologies, leading to perpetually low production partly attributed to persistent postharvest losses. Development agents can make use of various postharvest handling technologies, including cultural, mechanical, and chemical methods, that can be adapted to local and gender-specific contexts. By intervening with various techniques, postharvest losses can be effectively reduced.

Farmers often mishandle dry beans from harvest to storage, using inappropriate methods such as storing on the earth surface, in gunny bags placed on the floor, or in containers that do not control for weather fluctuations. This practice leads to losses due to poor quality grain that may be rejected in formal markets, including lucrative export markets. The problem extends to research gaps on the extent of bean losses due to poor quality grain. Literature on the extent of postharvest losses in dry bean grain handling is limited compared to maize, despite beans being a vital food crop in East

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Africa, that contributes significantly to household food security and Uganda's export earnings. A literature search yields a plethora of postharvest information on maize and a dearth of postharvest information on beans.

Postharvest literature extensively covers cereals (especially maize), high value crops (such as snap beans) and roots and tubers (such as cassava and sweet potato), but is relatively scarce on dry bean. Affognon et al. [23] revealed that out of 213 published articles, only 12 focused on dry bean, with five in Kenya, five in Tanzania, and two in Malawi. Compared to cereal grain, which has up to 15–50% postharvest loss [6, 24], losses in dry bean are not clear. Storage loss alone is estimated to be 8% in Kenya [25], and about 18% in Tanzania [26]. This information gap is significant for Uganda's policy discussions, since beans are a vital crop for feeding households, school children, refugees, and vulnerable populations.

Theoretical framework

This study employs a systems approach to analyse a specific phenomenon in a large system and its properties emerging from interactions of its elements [27]. To understand a phenomenon systematically, researchers must establish its relationships while considering boundary conditions and context [28]. Using systems practice, researchers can synthesize how others perceive the relationships and elements that make a difference in their context, while recognizing that the researcher's perspective also has an influence [4, 29]. In investigating PHL, the value chain can be seen as a human activity system where the activities cannot be separated from their specific situations, and their analysis can identify relevant boundary conditions that reveal actors' room for manoeuvre [29].

Conceptual assessment of postharvest losses

In general, food availability is hindered by losses that occur throughout the entire food production and consumption processes [3]. The study of postharvest losses involves analysing the losses that occur at every stage of production, which ultimately lead to a reduction in overall value and availability of food. Although there are various types of food losses and waste that occur after harvest, it can be challenging to determine what should be included in the PHL assessment [9, 29]. With a focus on staple commodities and storage losses, the term postharvest loss emerged to refer to "a measurable quantitative and qualitative loss in a given product... [and] restriction in the use of the product... [whereby] the sum of losses in quantity and quality of the products inevitably means losses of food and money" [30, 31]. Often, PHL and food losses are referenced to the early stages of the food chain, while food waste is referenced to later stages of the food chain [32]. However, the lack of consistent use of these terms in practice can make it difficult to assess postharvest losses [33, 34]. In this case, the losses in the food system are assessed based on space of a set of activities namely: production which occurs on the farm; value addition and marketing which are off farm; and finally, consumption points which occur at the households. The specific elements/activities within each subsystem contribute to variations in the losses in terms of available food, income and nutrition (Fig. 1). Therefore, we focus on postharvest losses within the farmer's space, which is a significant part of the overall food production continuum.
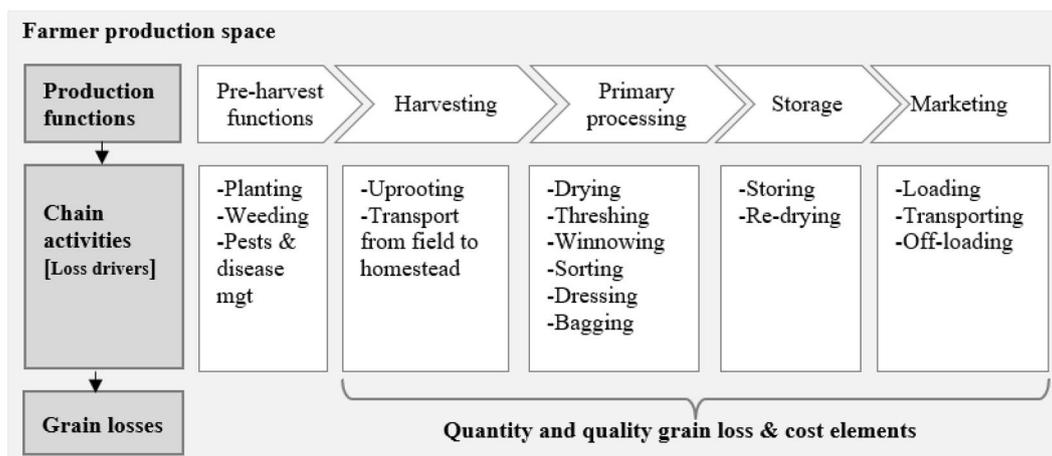

Fig. 1 Food system points and elements of food loss. Source: authors' conceptualization

Our key proposition was that postharvest losses of dry bean among farmers in Uganda existed and were partly aggravated by local farmer practices during storage. These practices affect the Moisture Content (MC) of dry beans during harvest, handling, and storage, leading to quality deterioration and economic losses. Postharvest loss (PHL) was defined as a proportion of total harvest lost due to spillage and physical damage. Grain quality is defined based on the MC parameter of bean samples, captured using digital moisture meters. We focused on three common storage methods used by many farmers, which include storage in a bag placed above ground, storage in a bag placed on the ground, and storage in containers. A good practice would be to keep dry beans at $\leq 13.0\%$ MC by controlling fluctuations in atmospheric relative humidity or dampness during storage. We used a generalized linear model to quantify the effects of smallholder storage practices on grain MC, after controlling for farmer and grain characteristics. This study contributes to more information on the extent of PHL and the degree to which smallholder farmer practices contribute to harvest and postharvest losses in pulse grains, and the implications for household food security.

Materials and methods
Materials
Study area, sampling, and sample size
The study was carried out across five districts situated in four regions of Uganda namely Nakaseke in Central region, Sironko in eastern region, Arua and Oyam in the Northern region, and Hoima in the Western region. These are the bean producing districts that were targeted by the NARO legumes program. One district was selected from each region, but in the Northern region, two districts were randomly sampled due to the considerable dispersion of farmers. Based on guidance from the district agricultural offices (DAOs), two major sub-counties known for producing common beans were sampled in each district.

Following a survey design, a cross-sectional data collection approach was used to obtain information from randomly selected farmers in the study areas. To achieve this, a multi-stage sampling process was implemented in line with local government structures in Uganda. In stage one, one district was purposively selected from each region, while stage two, sub counties were purposively chosen with the guidance of DAOs recommendation on areas with higher concentration of bean producing farmers. At stage three, two parishes were randomly sampled from each sub county, and two villages were randomly selected per parish. Finally, systematic random sampling approach was applied to choose ten farmers from each village based on the probability selection procedure,

$N_{village}/n$ where $N_{village}$ denotes the population of a selected village and where $n = 10$ to derive the nth interval selection from a village sampling list.

Data collection
Structured interviews were conducted with 445 farmers, and survey data was collected using computer assisted personal interviews (CAPI) and survey CTO application to obtain information on the preharvest, harvest, and postharvest practices implemented by a bean farmer. The distribution of the sample across the study sites is provided in Appendix Table 13. Bean samples were picked from the farmers who had dry bean grain in store at the time of the survey (June to August 2019). Out of the 445 farmers sampled; 324 farmers had bean grain in storage. Each collected sample was labelled and tagged with the farmer's unique identification number, and its MC was immediately measured using digital moisture meters. In cases where a farmer had more than one lot of dry beans in storage, up to three samples were taken. Overall, the analysis was based on 371 samples of dry beans.

Methods
Variable description and measurement
Preharvest, harvest and postharvest practices
This study examined the various practices that occur before, during, and after crop harvest. Preharvest practices include activities such as seed bed preparation, variety selection, planting, thinning, weeding, fertilizer application, and spraying. Harvest practices, on the other hand, pertain to the timing of the harvest, the methods used, and the handling of the crop after it has been harvested. Postharvest practices refer to a range of activities that occur in the food supply chain after harvest and before delivery to the market. For the purposes of this study, we focus on the activities and practices of producers/farmers from harvest to delivery to the market. Postharvest activities encompass transporting the harvest, drying, threshing, winnowing, sorting, storage, redrying after storage, and transporting the grain to the market. The timing and methods of each postharvest handling activity impacts the quality of the grain and lead to quantitative losses.

Storage practices
Grain storage involves various methods, treatments, and durations that vary among farmers. This study thus, examined five storage methods commonly used in the study area: gunny bags, containers, pics bags, pouring on the floor, and granaries. Farmers either raised the grain off the floor or placed it in direct contact with the floor. The analysis primarily focused on three traditional practices, which were adopted by more than 85% of farmers:

storage in gunny bags placed on the ground surface, storage in bags placed above ground, and storage in containers. The storage practices in pics bags ($n = 8$) and silos ($n = 3$) were not given extensive consideration beyond descriptive analysis due to their small sample size.

Postharvest losses

Postharvest loss within food systems refers to the loss of food in terms of quantity and/or quality along the entire food supply chain, from harvest to the point of consumption [35]. Quantitative losses occur when the actual amount of food, often measured in either kilograms or calories, reduces over time and space [12]. On the other hand, qualitative losses may result from contamination of food or via nutrient loss. Qualitative losses are more difficult to detect compared to quantitative losses, but potentially more important due to micronutrient loss and food safety concerns leading to a high prevalence of micronutrient deficiencies and food-borne health hazards around the world than undernourishment due to insufficient dietary energy intake [12, 36]. Measurement of quantitative losses remains a challenge, particularly among smallholder farmers and informal value chain actors who often do not care much about quality and record keeping. There are various approaches available for measuring quantitative food losses, leading to varying estimates for the same commodity in context. Some studies have used the self-reporting approach for the smallholder subsistence farmers. For instance, Chegere [6], Shee et al. [37] and Debebe [8] used the self-reporting approach which relies on farmer experience and judgment to estimate PHL in grains. Indeed, acknowledging the constraints of self-reporting approach and the reliance on farmer experience in bean production, we utilized this method to gather information on the physical/mass losses of bean grains, measured in kilograms, at every stage of handling. To enhance the dependability of our findings, we restricted our inquiry to the most recent farmer harvest, which took place two to four months before the survey. The quantities lost were then computed at each stage as a proportion of the harvest (Eq. 1):

$$L_{ps} = \frac{1}{N} \sum_{i=1}^{N} Q_i / Y_i \tag{1}$$

In this case, L_{ps} denotes proportion of beans lost derived from quantity Q of beans lost at a particular handling stage (s) divided by quantity harvested Y computed at the mean for N sample of farmers, $i \in \{1, 2, \ldots N\}$. All weight measurements were captured in kilograms.

The value of grain loss was computed as a product of quantity of produce lost and price (Eq. 2) taken at the mean. The price considered is the price that a farmer i reported for the quantity sold:

$$L_{vs} = \frac{1}{N} \sum_{i=1}^{N} Q_i * p_i \tag{2}$$

where L_{vs} denotes value of quantity of beans lost at each handling stage (s) expressed as a product of quantity Q lost and price p offered for beans that were sold.

Moisture content

Moisture content is the amount of water in grain usually expressed as a percentage of the grain weight and it was captured on a wet basis approach using digital moisture-meters that had been validated at the research station prior to conducting the exercise. The MC readings were captured in the field and appropriately labelled with household identifiers.

Empirical approach
Selection and measurement bias

Due to the use of cross-sectional data collected from farmers, it was the authors considered opinion that the assignment of practices to respondents was random given a farmer's voluntary choice to adopt a practice within the resource constraints and information barriers that also randomly vary. In this case, selection bias is thought to be negligible because there was no strategic external farmer selection into technology users' category which often arises when a project targets a section of farmers in an intervention area. In addition, bean samples that were used for measurement of MC were random elements from a subset of farmers who affirmed that they had some beans in storage and even then, some farmers had more than one batch of dry beans in storage, and samples from all varieties were collected. Furthermore, we avoided bias in bean sample selection by using all the collected samples that were picked from the surveyed farmers. This also helped to avoid a drop in the study sample size, and allowing for better estimates. For regression estimates, the response variable was MC, and we addressed bias due to omitted variables, model specification, and measurement errors through a two-step regression and maximum likelihood estimation. In the first step regression, the aim was to partial out the error term, and in the second step, the error term was introduced as one of the predictors of variation in MC of farmer bean grains. This approach enabled us to account for specification bias due to unobserved factors and control for endogeneity in the final specification of the model.

Modelling the effect of storage practices on moisture content of stored dry bean

The objective was to assess how different storage practices impacted the MC of dry beans stored under farmer conditions. Since MC was measured as a proportion, it represents a bounded continuous response variable, which requires an estimation approach that accounts for the closed interval. While some studies have used fractional response models or the ordinary least squares (OLS) estimation approach on bounded data, these approaches pose a risk of producing biased estimates due to violations of the underlying model assumptions and possible predictions outside the boundary limits. [38, 39]. Most linear estimation tests are based on the *t* test which relies on the assumption that there is normality in the conditional distribution of the outcome variable *y*, $f(y|x)$ is $N(\mathcal{K}(x), \sigma^2)$. This is not applicable for a variable that has a closed interval, such as MC that is the subject of investigation in this study. According to Kieschnick & McCullough [40] and Gray & Alava [38], linear estimation on a bounded dependent variable can violate two conditions: the conditional expectation function $(E(y|x) = \mathcal{K}(x) = x'\beta)$ which in our case was nonlinear, since it maps onto a bounded interval; and the variance of *y* (MC) must be heteroskedastic since the variance approaches zero as the mean gets to the boundary point. The problem could be lessened with larger sample sizes where asymptomatic arguments can be rationalized. However, our data sample size ($n=371$) could not warrant the invocation of asymptomatic arguments to rationalize the less stringent characterisation of the regression model.

Econometric model

In this case, MC, measured as a proportion, and had values ranging from 0 (as minimum) to 1 (as maximum bound). Therefore, the observed distribution of MC, *y*, is within a closed interval, meaning that its conditional expectation was nonlinear, and its conditional variance was a function of the mean. To account for these characteristics, a generalized linear model (GLM) using the beta distribution was preferred for regression analysis. The beta regression assumes a distribution for the response variable, *y*, based on selected covariates, and its parameters are estimated using maximum likelihood principle. Unlike the fractional response model, the beta regression model is a member of the exponential class of distributions, and so, maximum likelihood estimators have established statistical properties in this class of distributions [41]. Equation 3 expresses the mean and variance of the conditional distribution of y, which is modelled using the beta distribution. One limitation of this model is that if

the distributional assumptions are mis-specified, it can result in inconsistent estimates of the model parameters [40].

To obtain a regression structure for the mean of the response along with a precision parameter, the mean is expressed as $\mu = p/(p+q)$ and the precision parameter $\phi = p + q$ and by substitutive algebra, $p = \mu\phi$ and $q = (1 - \mu)\phi$:

$$E(y) = \mu_i \quad \text{for } p < \mu < q$$

$$var(y) = \frac{V(\mu)}{1 + \phi} \quad \text{for } V(\mu) = \mu(1 - \mu) \text{ and } \phi > 0 \tag{3}$$

where $V(\mu) = \mu(1 - \mu)$, so that the mean μ of the response variable *y* (MC) and ϕ is interpreted as a precision parameter in the sense that, for fixed μ, the larger the value of ϕ, the smaller the variance of *y*. The density of *y* is represented by a new parameterization expressed in the following equation:

$$f(y; \mu, \phi) = \frac{1}{B(p,q)} y^{p-1} (1 - y)^{q-1}, \quad 0 \le y \le 1 \tag{4}$$

where $0 \le \mu \le 1$, $y \in \{p, q\}$, and $B(p, q)$ is a beta function. This distribution is the most fitted to proportional data, has most empirical support, and is in the class of exponential distributions, which are the basis for the generalized linear model paradigm [40, 42]. As revealed by Cox [43], a Logit link specification is used such that conditional expectation is expressed, as shown in the following equation:

$$E(y_i|x_i) = \mu_i = h(\eta_i) = \frac{1}{1 + \exp(-\eta_i)} = \frac{1}{1 + \exp(-x_i'\beta)} \tag{5}$$

The variance of *y* is a function of the mean μ and decreases as the precision parameter ϕ increases. It should be noted that the beta densities can display different shapes based on values of the two parameters: mean (μ) of *y* and the precision parameter (ϕ) [38, 39]. Furthermore, it is worth emphasizing that when the mean (μ) is held constant, the dispersion of the beta distribution decreases as the precision parameter (ϕ) increases. To accommodate our distributional model, Eq. (5) was reformulated, as shown in Eq. (6). This equation demonstrates that the conditional mean of a beta-distributed regress and is limited to the interval (0, 1), which is suitable for our model, since the response is constrained to the standard unit interval (0, 1). The model can also be applicable in scenarios where the response is restricted within a known scaler interval (a, b), where a and b are known values and $a < b$. In that case, *y* is indirectly

modelled as a transformed variable $y^T = (y - a)/(b - a)$ with $0 < y^T < 1$ with a standard beta distribution having a mean$(\mu - a)/(b - a)$. The $y_1, \ldots, y_n$ would represent independent random variables, where each $y_\sqcup$, $\sqcup = 1, \ldots, n$, follows the density in Eq. (1) with mean μ_i and unknown precisionϕ. The model is derived by assuming that the mean of y_i can be defined by the expression in Eq. (6). This means that if the response variable (y), such as MC, is not specified within the interval $(0, 1)$ but rather within a different range (a, b), as may happen if MC is expressed in percentages instead of proportions, the model would not require adjustments for misspecification.

$$g(\mu_\sqcup) = \ln\left(\frac{\mu_i}{1 - \mu_i}\right) = \sum_{i=1}^{k} x'_{\sqcup i}\beta_i = \eta_\sqcup \qquad (6)$$

where $\beta = (\beta_1, .., \beta_k)^T$ is a vector of unknown regression parameters ($\beta \epsilon \mathbb{R}k$) and $x_1, \ldots, x_{\sqcup k}$ are observations on k covariates ($k < n$), assumed to be fixed and known. Finally, $g(.)$ is a strictly monotonic and twice differentiable link function that maps $(0, 1)$ into $\mathbb{R}$. Note that the variance of $y_\sqcup$ is a function of $\mu_\sqcup$ and, consequently, of the covariate values. Hence, non-constant response variances are naturally accommodated into the model. The relationship in Eq. (6) relates to the parameters of the beta distribution. Through Eq. (1), we have $E(y_i) = \frac{p}{p+q}$, and then, $x'_i\beta$ is mapped into q because q is the shape parameter for the beta distribution. q is then expressed as shown in Eq. (7) that is consistent with expectation $E(y_i) = \mu_i$:

$$q(x_i) = p\exp(-x'_i\beta) \qquad (7)$$

Through substitution of expression for q into Eq. 4, a conditional distribution of the beta distributed random variate is derived. For brevity, the derivation is not presented. To estimate the effect of the various conditioning variables ($x_1, x_2, \ldots, x_r$), a maximum likelihood estimation principle is applied to arrive at the estimates of the vector β by maximizing the implied log-likelihood function with respect to the parameters β and p. To select a model within the family of GLM regression, we rely on Akaike Information Criteria (AIC) while goodness-of-fit is assessed based on the Pseudo R^2, and Wald chi test.

Model specification

To assess marginal effects of storage practices on grain MC, the outcome variable y is denoted by mc_i which means MC of a bean sample i observed and captured in the field. Estimation is operationalized through a beta fit regression without bothering about a mixed distribution, since our response variable is not defined at 0 but in the interval $[\tau, 1]$ which means that the beta distribution is only defined in the interval $[\tau, 1]$ and can be captured in a single beta distribution. The model was operationalized through the empirical expression, as shown in the following equation:

$$\begin{aligned} E(mc_i; y|x) = h(&\beta_0 + \beta_1 \exp + \beta_2 \sex + \beta_3 \mathrm{accInfo} \\ &+ \beta_4 \mathrm{gsize} + \beta_5 \mathrm{dharv} + \beta_6 \mathrm{sp1} \\ &+ \beta_7 \mathrm{sp2} + \beta_8 \mathrm{sp3} + \beta_9 \partial) \end{aligned}$$

$$(8)$$

where mc_i is moisture content (y) of a random bean sample that was picked from a farmer and measured as a proportion to fall within the interval $(0,1)$. The mc_i is conditioned to vary considering heterogeneity in farmer experience (*exp*), sex (*sex*), farmer access to information on bean production (*accInfo*), grain size which varies by bean variety (*gsize*), practice of delayed harvest (*dharv*) and the adopted storage practice (*sp1, sp2,* and *sp3*). β_0 denotes a constant term associated with y intercept of the model estimation.

The model incorporates farming experience and information access, assuming that they have a positive association with MC. Existing literature suggests that farming experience frequently leads to favourable production outcomes for farmers [44]. Furthermore, the gender of the farmer is incorporated into the analysis, since previous research has demonstrated that gender significantly impacts the acceptance and adoption of agricultural technologies in Uganda [45, 46]. To account for unobserved variables and endogeneity biases, we incorporated ∂ in the analysis.

Data and variable characteristics.
Data description
Primary cross-sectional data were collected from 445 farmers and descriptive analysis was conducted on production practices using this sample size. All analyses related to MC were performed on 371 bean samples that were obtained from some but the same group of farmers. This approach helped us prevent any selection bias in the choice of bean samples for analysis and ensured that we did not diminish the sample size. To accomplish this, we transformed the data and utilized a long-format for analysis instead of a wide-format.

Variable characteristics
Farmer sex, household headship, and gender of the household head were represented using dummy variables. On the other hand, we captured farmer marital status, education level, farmer occupation, and household type as multiple categorical variables. Table 1 and Appendix Table 14 presents summary statistics of the

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Table 1 Descriptive statistics of selected variables

Variable	Description/Unit	Mean	Std. Dev	Min	Max
Age of household head	Number of years	43.7	12.40	21	80
Farmer schooling	Number of years	7.6	3.40	0	18
Experience in bean production	Number of years	17.6	12.14	1	57
Household size	Number	7.1	3.39	1	33
Female household members	Number	3.6	1.94	0	16
Male household members	Number	3.5	2.19	0	17
Available/accessible land size	Hectares	4.5	3.75	0.5	25.0
Land allocation to dry bean	Hectares	0.3	0.30	0.02	4.86
Proportion of land allocation	Proportion	0.4	0.25	0.03	1.00
Access to agronomic information	Dummy	0.3	0.44	0	1
Access to bean PH information	Dummy	0.1	0.33	0	1

Source: Field study, 2019

sample socio-economic characteristics. The results reveal that men were the primary household heads, and 72% of the household heads were married. In addition, around 59% of the household heads had only attained primary level formal education, and 64% engaged in agriculture as their primary occupation. These statistics are consistent with national averages, which suggest that most households in Uganda rely on agriculture as their primary livelihood strategy [47]. This can be attributed to the limited livelihood opportunities outside the rural farm economy, which is partly a result of the low education levels. Furthermore, this could also be a factor that influences farmers' access to post-harvest technologies (refer to Appendix Table 14).

Farmer age, farming experience, and years of schooling were represented as discrete continuous variables measured in complete years. Land size was measured in hectares. As presented in Table 1, the average age of household heads was 44, with about seven years of schooling. The households, on average, comprised of seven family members. Most of the farmers had over 17 years of experience in bean production, and the average land allocated for bean production was approximately a quarter of a hectare, which is approximately 0.5 acres. This constituted 40% of the arable land accessible to the household, regardless of the mode of access.

Results
Preharvest practices employed by farmers in common bean production
We found that most farmers (81%) cultivated dry beans during the second cropping season, which spans from August to December, while roughly 23% grew dry bean during the first cropping season (Table 2 and Fig. 2). A small proportion of farmers (23%) had planted improved seeds. Most farmers planted beans in rows, and only about 11% had planted at least two different bean varieties. Bush beans were found to be the predominant type of bean grown in the surveyed areas.

Fertilizer and pesticide application in bean production were low and about 65% of the farmers practiced intercropping with dry bean as the dominant crop in the plot. Many farmers recycled the seed for an average of about 10 years. In addition, majority of the farmers planted beans during the second cropping season, spanning from August to December, with planting peak in October (Fig. 2). It is worth noting that a significant number of farmers planted their crops within the same time frame, which could affect their access to labour for planting, harvesting, and postharvest handling. In addition, the planting of several crops simultaneously can constrain timely harvesting and proper postharvest handling practices.

Harvest and postharvest practices
Harvesting practices
Smallholder farmers in the studied locations harvested dry bean by uprooting the entire plant when considered mature enough. Typically, farmers harvest the crop when the plant was completely dry. However, about 41% of farmers reported delaying harvest, and 34% of them delayed harvest by more than two weeks (Table 3). Following harvest, approximately 80% of the farmers transported the beans to their homesteads and heaped them in preparation for threshing.

Postharvest practices
Farmers engage in several postharvest activities for dry beans, but many of these activities are labour-intensive,

Table 2 Descriptive statistics of preharvest bean practices employed by the interviewed farmers

| Variable	Mean (N = 445)	St. Dev	Min	Max
Crop production season (proportion)				
Season 1 (March–July)	0.23	0.420	0	1
Season 2 (August– December)	0.81	0.393	0	1
Season 1 and 2	0.038	0.192	0	1
Planted improved seed	0.27	0.443	0	1
Planting method (proportion)				
Manual row planting	0.64	0.480	0	1
Manual broadcasting	0.36	0.480	0	1
Number of varieties planted (proportion)				
One variety	0.83	0.380	0	1
Two varieties	0.15	0.358	0	1
Three varieties	0.25	0.156	0	1
Type of bean by growth habit (proportion)				
Bush type	0.98	0.133	0	1
Climber	0.01	0.115	0	1
Semi-climber	0.08	0.269	0	1
Quantity of seed planted (Kkgha-1)	62.613	62.012	0.705	67
Practice intercropping	0.626	0.484	0	1
Proportion of beans in intercropped plot (mean)	0.655	0.143	20	95
Applied fertilizer	0.060	0.237	0	1
Applied pesticides	0.225	0.418	0	1
Years of seed/variety recycling (mean)	9.746	9.072		

Source: Field study, 2019
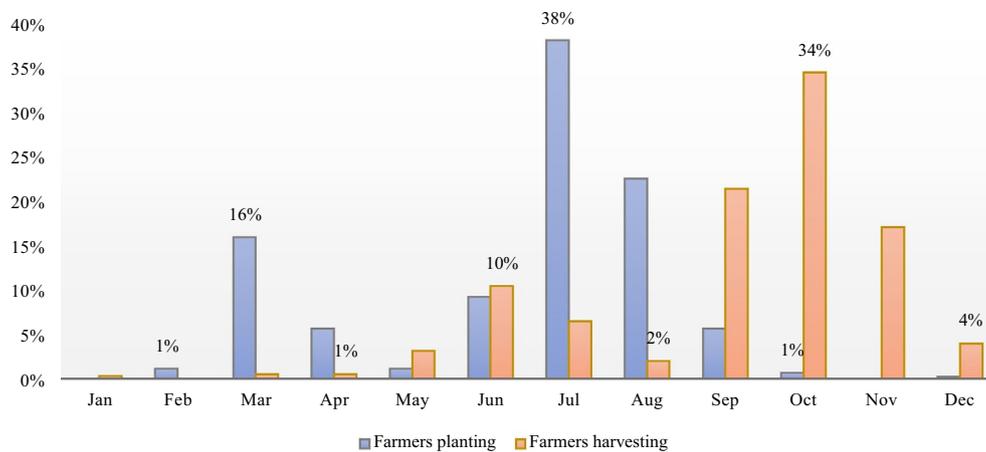
Fig. 2 Percent of farmers that planted/harvested common bean in the month of the year. Source: Field study, 2019

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Table 3 Proportion of farmers who employed the various harvest and post-harvest practices

Harvest practice	Percent of farmers
Stage of harvest	
Physiological maturity	27.0
Morphological maturity	5.4
Beyond morphological maturity (completely dry plant)	83.8
Delayed harvest when crop had reached maturity	40.5
Duration of delayed harvest	
0–6 days	66.1
7–14 days	25.6
15–30 days	8.3
Handling of crop immediately after harvest	
Transported and first kept in a heap and awaited threshing	78.7
Threshed in the field immediately after harvest	26.1
Heaped in the field and awaited threshing	2.5

Source: Field study, 2019

Table 4 Farmer postharvest practices

Post-harvest practices and methods	Percent of farmers
Drying of pods off-field	82.3
Threshing	98.4
Winnowing	91.7
Sorting of beans	45.6
Grain dressing/treatment	23.6
Bagging	22.3
Storage and structure	80.7
Farmers with a produce storage facility	54.2
Store in same sleeping house	89.3
Store in stand-alone storage structure	9.3
Store in a granary	0.0
Store in another place	2.2
Storage practice and facility	
Stored in gunny bag placed on cement floor	45.7
Stored in gunny bag raised above ground	11.8
Stored in gunny bag placed on earth floor	5.9
Stored in containers (plastic basins, buckets, tins)	5.7
Stored in improved/PICs bag	2.1
Silo	0.8
Tarpaulins	0.6
Practice natural grain drying after harvest	76.0
Secondary processing of grain	0.0
Proper packing/ Bagging	57.5

Source: Field study, 2019

leading some farmers to partially complete or skip some tasks altogether (Appendix Table 15). Some of the most common postharvest activities include drying, threshing, and winnowing (Table 4). However, a significant percentage of farmers did not sort or treat their dry beans, possibly due to labour constraints.

Crop output, postharvest handling expenditure, and losses
Harvested quantity and disposition of output
Results in Table 5 show that approximately 76% of the harvested produce was disposed by selling in the market, whereas 13% was consumed at household. The average estimated value of harvest per hectare was US$ 607, calculated based on an average unit price of approximately US$ 0.56 (≈UGX 2000) per kilogram.

Expenditure on harvesting and postharvest handling activities
Table 6 shows that farmers were involved in various production activities, starting from harvesting to consumption of their products. Based on an average yield of 1080 kg per hectare of dry beans, the cost of postharvest processes was found to be US$ 57, which represented approximately 13.5% of the total value of the produce. Among the various production activities, the highest expenditure was incurred on harvesting, accounting for 59% of the total cost, followed by threshing, which accounted for 12% of the total cost (Table 6).

Postharvest grain losses
Farmers experienced losses of up to 22% of the harvested bean grains quantity due to various handling issues that occur throughout the entire process, from harvesting to marketing. Appendix Table 16 presents the details of grain losses incurred by farmers in four stages, namely harvesting, primary processing, storing, and marketing. Figure 3 illustrates that the highest percentage of grain loss occurred during primary processing (~ 12%), followed by harvesting (4.1%), threshing (3.7%), and sorting (3.6%) stages.

Value of postharvest grain loss
According to the results, threshing (3.7%), sorting (3.6%), and storage (3.4%) were the stages with highest monetary losses, while dressing had the least loss (0.3%). This indicates that inappropriate postharvest handling can result in the loss of valuable quantities

Table 5 Share of harvest, quantity of beans harvested and used for different purposes

Variable	Share of harvest	Average	Std. Dev	Min	Max
Quantity harvested (ha^{-1})	1.00	1080.5	570.819	15.253	2337.122
Quantity sold	0.76	838.9	574.323	0.000	2265.052
Quantity consumed at household	0.13	124.0	234.873	0.000	2223.870
Quantity used for seed	0.05	55.0	109.855	0.000	1098.207
Quantity used for other purpose	0.05	62.6	167.257	0.000	1310.222
Price per Kg (US$)	-	0.55	0.167	0.215	1.076
Value of crop (US$)	-	607.18	391.820	8.207	2297.841

US$ denotes United States Dollar while UGX denotes Uganda shillings currency. Harvest is valued in US$. The exchange rate is US$ 1 = UGX 3717.23 which was the Bank of Uganda average for June–August 2019. Source: Field study, 2019

and grain quality, which can lead to lower price offers, rejection of grain, and higher economic losses. Poor quality beans delivered to some buyers resulted in farmers facing a price penalty. Based on the findings, it was determined that the farmers lost up to US$ 0.14 (≈UGX 500) per Kg due to lower price offers associated with grain quality, translating into a 26% price penalty loss on every kilogram (Table 7). The loss of produce quality is often associated with physical damage on grain, foreign material and mixing of varieties.

Table 8 reveals that farmers experienced an economic loss of US$ 103 per hectare, which accounts for roughly 17% of the crop's total value, due to grain losses during various postharvest operations. The harvesting stage had

Table 6 Share and cost of harvesting and postharvest handling practices

Activity	Share	Mean (US$/ha)	Std. Dev	Min	Max
Harvesting	0.588	27.206	30.925	0.821	327.454
Drying pods	0.017	1.698	5.970	0.000	53.179
Threshing	0.116	9.062	16.975	0.000	158.27
Winnowing	0.035	4.160	16.339	0.000	253.231
Sorting	0.058	3.948	15.260	0.000	253.231
Treatment	0.023	1.607	5.789	0.000	63.308
Bagging	0.070	2.545	2.449	0.000	19.647
Storing	0.026	2.771	14.422	0.000	196.473
Further drying	0.006	0.497	2.756	0.000	32.826
Secondary processing	0.000	0.000	0.000	0.000	0.000
Other	0.000	0.014	0.224	0.000	4.103
Transporting	0.039	2.605	7.168	0.000	82.066
Re-bagging	0.022	1.178	4.212	0.000	63.308
Total cost (U$)	100.0	57.291	73.540	1.641	870.483
As share of output value	0.135	0.135	0.229	0.007	3.067

Costs are computed in Uganda shillings. Consider an exchange rate of US$ 1 = UGX 3,717.23. Source: Field study, 2019

the highest loss in value terms, amounting to US$ 22 per hectare, followed by threshing, sorting, and storage.

Storage practices and moisture content
Farmer test for moisture content
Smallholder farmers typically rely on subjective methods to determine the dryness of their grain, using personal judgment based on organoleptic tests that involve primarily seeing, feeling, and hearing. As shown in Table 9, most farmers (51%) used the method of biting the grain to assess whether it was dry enough for storage. During the biting process, farmers took note of the hardness of the grain and the sound it made. Some farmers also used a combination of visual inspection, shaking a sample of the grain, or pressing it with a finger or nail to test its hardness, in conjunction with feeling or hearing the sound made when cracking or rattling.

Interestingly, the study found that only a small fraction of farmers (about 2%) used non-subjective methods to test the dryness of their grain, such as moisture meters or the bottle approach. Under the bottle approach, farmers place the grain in a bottle and leave it in the sun. If moisture is noticed on the inner surface of the bottle, then the grain is considered not fully dry. Some farmers add salt to the bottle and use the amount of moisture noticed on the bottle to determine whether the beans are well-dried. Notably, only farmers who tested beans using the non-subjective method had a MC of less than or equal to 13.0%.

Storage practice
Roughly 12% of the farmer bean samples came from bags that were stored above the ground, while 46% reported storing their bean grain in bags placed on a cemented floor (Table 10). In addition, the results indicate that the MC of bean grains stored in bags placed on cement and earth floors (∼ 15%) was higher than that of bean grain stored on a raised platform (∼ 14%).
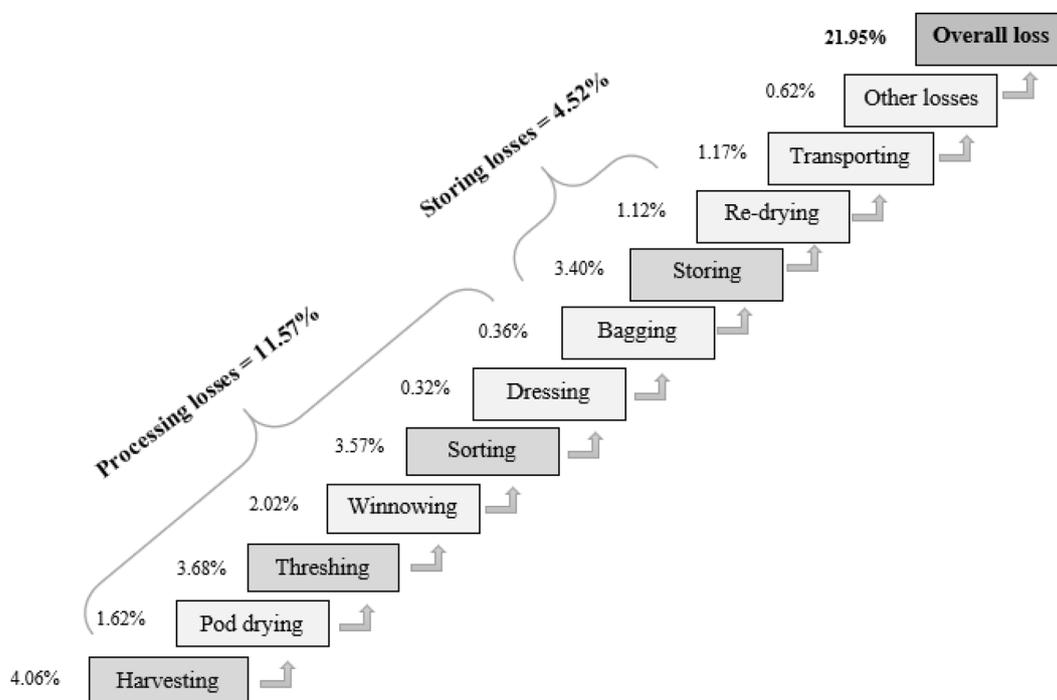
Fig. 3 Grain losses of common bean at various nodes of postharvest handling. Source: Field study, 2019

Table 7 Market price and lost premium in price offer

Variable	Mean	Std. Dev	Min	Max
Unit selling price (UGX/Kg)	2064.831	621.489	800.000	4000.000
Selling price (in U$)	0.555	0.167	0.215	1.076
Price penalty due to poor quality grain (US$)	0.140	0.085	0.000	0.377
Loss in pricing due to poor quality (proportion)	0.259	0.161	0.000	1.000

UGX denotes Uganda shillings. The penalty on price is a difference between actual selling price and reported difference with other farmers due to quality difference.
Source: Field study, 2019

Storage duration and moisture content

Table 11 displays results on the storage duration and average MC of collected bean samples. The dry bean samples from farmers were divided into two groups based on their MC levels: > 13.0% and ≤ 13.0%. The results showed that 51% of the bean samples were stored for 1–30 days and had an average MC of 15.0%. However, after 31–60 days of storage, the bean samples had a MC of 14.6% and samples stored for over 60 days had an even higher MC (15.2%) than those stored for ≤ 60 days. The study also revealed that the mean MC of samples from farmers who met the standard of ≤ 13% MC was significantly lower than that of farmers who did not meet the standard MC level, at various storage durations (Table 11).

Figure 4 shows that the required MC was only met by approximately 26% of the bean grains from 371 samples.

The data also indicates that 31% of the grain owned by women met the standard MC, which is significantly higher than the 23% of the grain that was owned by men.

Storage practice, storage duration, and predicted moisture content

Overall relationship between predicted MC and storage duration

Upon predicting the MC of the bean grains and plotting its fitted values against the storage duration under farmer conditions, it becomes apparent that the MC of grain in storage registers a gradual drop to a point and starts to exceed the recommended level of ≤ 13% after about 60 days. In Fig. 5, the MC drops gradually up to approximately 14.2% at 60 days of storage, but then begins to increase beyond this point considering the local farmer practices and conditions of exposure grain is subjected

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Table 8 Value of grain lost during harvesting and postharvest handling

Activity	Mean (US$/Ha)	St. Dev	Min	Max
Harvesting	21.556	39.626	0.000	437.410
Drying podded grain	7.161	13.045	0.000	132.947
Threshing	17.817	18.517	0.164	122.232
Winnowing	8.408	14.603	0.103	201.385
Sorting	17.732	18.698	0.000	122.232
Treatment	1.346	4.913	0.021	93.063
Bagging	1.286	2.703	0.021	37.985
Storing	17.195	18.423	0.164	122.232
Grain drying	4.232	9.169	0.033	123.099
Secondary processing	0.000	0.000	0.000	0.000
Other	0.489	0.903	0.011	12.280
Transporting	4.596	9.272	0.083	100.120
Re-bagging process	1.585	4.032	0.000	99.476
Value of grain lost (U$)	103.196	106.493	2.502	797.207

Source: Field study, 2019

to. Given the grain standards stipulate a maximum MC of

Table 9 Farmer methods of testing grain for dryness

Practice/ method	Percent of farmers	MC of grain at ≤ 90 days of storage			
		Mean	SD	Min	Max
Biting the grain	51.0	15.23	3.13	9.5	26.3
See and feel	21.8	14.83	3.14	8.1	26.8
Shake and hear	17.5	14.63	2.99	9.1	21.7
Press and feel	2.9	13.78	1.84	11.1	17.0
Base on drying period	2.7	14.04	1.03	12.3	16.5
Bottle method	1.4	12.90	2.39	10.0	15.5
I don't know	0.7	17.10	1.97	15.5	19.7
Moisture meter	0.7	19.25	1.26	18.1	20.4
Ensure harvest when grain is dry	0.7	12.33	2.57	10.1	15.7
Tell from the leaves in the field	0.4	–	–	–	–
When beans begin to shatter	0.2	14.40	0.00	14.4	14.4

Farmers who used the moisture meter had no bean samples at time of the interview. Source: Field study, 2019

13% for export-grade dry beans, the findings suggest that farmers could store their dry beans for not more than 60 days and then sell them, particularly if they intend to target formal markets.

Comparative relationships on storage duration and storage practices

Table 10 provides further insight into the relationship between storage duration and storage practice, which is also graphically illustrated in Fig. 5, where the predicted

Table 10 Moisture content of bean grain stored by farmers under different storage practices

Storage practice	Proportion (*n* = 371)	Mean values	
		MC (%)	Storage days
Overall (pooled sample)	1.000	15.0 (0.105)	79.62 (2.888)
Store in bags placed cemented floor	0.457	14.8 (0.145)	45.39 (1.702)
Store in bags placed above ground	0.118	14.3 (0.240)	38.30 (1.649)
Store in bags placed on earth floor	0.059	14.7 (0.331)	38.29 (4.660)
Store in bags placed on tarpaulin	0.006	13.4 (1.431)	25.50 (2.012)
Store in plastic containers/tins	0.068	15.3 (0.356)	56.45 (9.165)

MC denotes moisture content recorded as a proportion; and values in parenthesis are standard errors. Source: Field study, 2019

MC is plotted against the storage duration. For the bean samples collected, the trend shows that the MC dropped as the storage duration increased up to a certain point, after which it begun to rise again (Plot line 0). For the bean grain that was placed on either a cemented floor or an earth floor (represented by plot line 1 and 3), the MC level gradually decreased with increasing storage duration, but only to a level not below the required MC of 13%, and then it started to increase again. On the other hand, when the grain was stored in bags placed above ground (storage practice 2), the MC dropped to levels close to 13% as the storage duration increased, but then it started to rise again after 60 days. It is worth noting that the likelihood of the MC dropping to 13% increases as the storage duration extends to several days, but not exceeding 60 days. Furthermore, the MC dropped more quickly when the grain was stored in bags raised above ground, as compared to other storage practices. In light of these findings, it is conceivable that farmers should store their grain for less than 60 days, as the MC of the stored grain under farmer conditions is likely to increase after this period, leading to deterioration and economic losses resulting from poor quality.

Effect of storage practices on moisture content and storage duration

Goodness-of-fit

To begin, a linear regression (OLS) was conducted. However, based on the results of the Shapiro–Wilk and the Breusch-Pagan het-test, it was discovered that the error terms of $y(mc)$ were not normally distributed and were non-homoscedastic, indicating that nonlinear estimation techniques would be better suited for the analysis than

Table 11 Moisture content of bean grain stored by farmers under different for durations

Storage duration	Obs (n = 371)	Mean moisture content (%)			p-value
		Overall	Farmers with ≤ 13% MC	Farmers with > 13% MC	
01—30 days	51.2%	15.0 (0.143)	11.2 (0.113)	16.3 (0.129)	0.0000
31—60 days	21.3%	14.6 (0.222)	11.1 (0.166)	15.9 (0.215)	0.0000
61—90 days	04.8%	15.2 0.286)	11.5 (1.450)	15.4 (0.268)	0.0042
91 & > days	22.3%	15.2 (0.247)	11.8 (0.122)	16.6 (0.272)	0.0000

The number of observations is based on the number of bean samples; MC denotes moisture content; and values in parenthesis are standard errors. Source: Field study, 2019
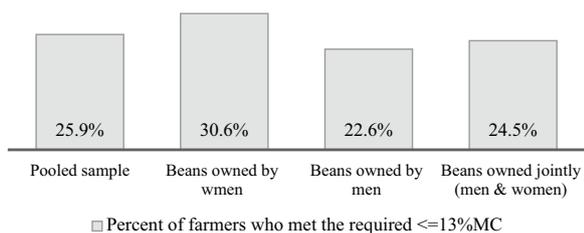
Fig. 4 Proportion of farmers meeting the moisture content standard. Source: Field study, 2019

the linear related estimations such as the least squares, censored normal, and the additive logistic regression models. The heteroskedasticity of the bounded error distributions was observed because their conditional variance must approach zero as their conditional mean approaches either of their boundary points. Therefore, the functional form of the dependent variable could not be supported by linear estimation. In addition to the linear regression, *glm*, *betareg*, *betafit*, and *betamix* regressions were also conducted, and based on the AIC factor, the betamix regression was deemed to be the most appropriate (Appendix Table 17). To verify the absence of multicollinearity, the variance inflation factor (*VIF*) was calculated and found to be less than the threshold value of 5. The results in Table 12 shows the partial derivatives of the conditional expectation of the nonlinear regression model, with respect to the GLM regression based on a beta distribution, with coefficients evaluated at the means, for ease of interpretation.
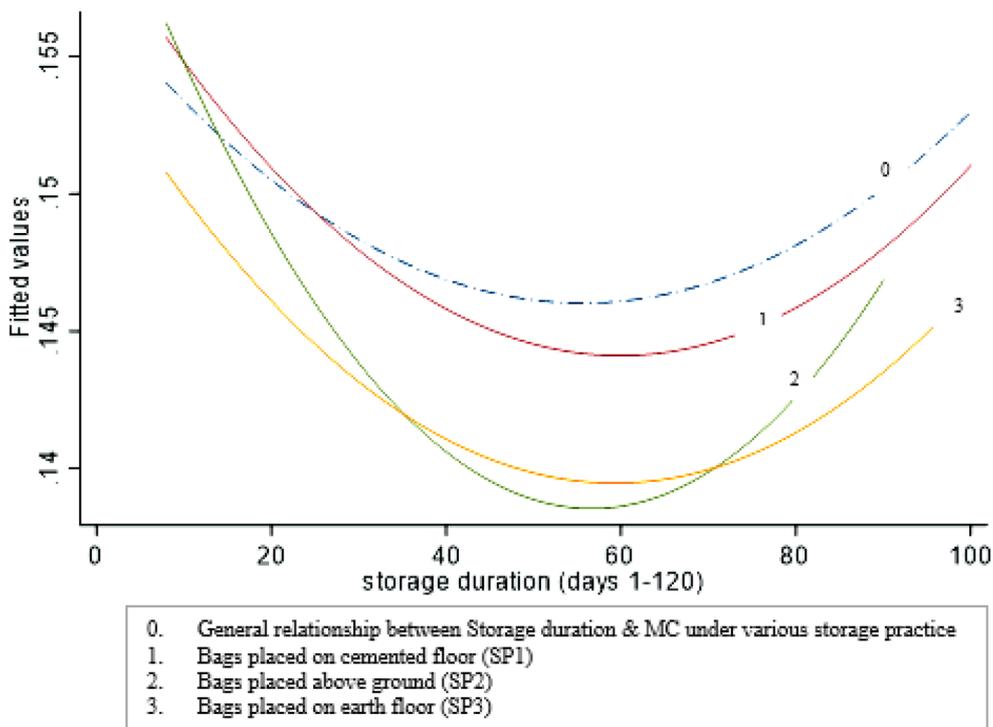
0. General relationship between Storage duration & MC under various storage practice
1. Bags placed on cemented floor (SP1)
2. Bags placed above ground (SP2)
3. Bags placed on earth floor (SP3)

Fig. 5 Relationship between moisture content and storage duration for each farmer storage practice. Source: Field study, 2019

Table 12 Multivariate GLM regression results of factors influencing bean grain moisture content

Explanatory variable	Marginal effects (SE)
Farming experience (Years-log)	− 0.0011 (0.0011)
Sex of produce owner (1 = woman, 0 otherwise)	− 0.0066** (0.0024)
Access to production information (1 = Yes; 0 = No)	0.0072** (0.0022)
Grain size (1 = medium to large, 0 = small)	− 0.0035 (0.0028)
Delayed harvest (1 = one week; 0 = > 1 week)	− 0.0036 (0.0025)
Storage duration (days—log)	− 0.0026** (0.0011)
Store in bags placed on cemented floor (sp1)	− 0.0098*** (0.0026)
Store in bags placed above ground (sp2)	− 0.0152*** (0.0033)
Store in bags placed on smeared earth floor (sp3)	− 0.0100*** (0.0047)
Unobserved factors	0.2535 (0.3572)
Constant	–
Ln phi = 4.9187*** (0.073) Number of observations (N) = 371	

Note: Values in parenthesis are standard errors (SE); ***Significance at 1% (p < 0.01) and **Significance at 5% (p < 0.05)
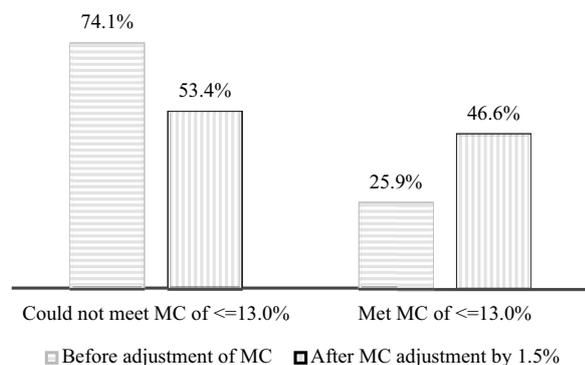
Source: Field study, 2019

Fig. 6 Percent of farmers who could meet MC requirement if they grain would be place above surface. Source: Field study, 2019

Empirical results

The regression output revealed that both farmer traits and farmer practices significantly affected the MC of bean grain (Table 12). Certain farmer factors were found to have a negative correlation with grain MC, such as experience in bean handling (using the farmer's experience in bean production as a proxy), ownership of grain by women, and delayed harvest. On the other hand, some farmer storage practices were found to have a negative correlation with MC, including storage in bags above ground, on cemented floors, and on smeared earthen floors. In contrast, access to general production information and grain size exhibited a positive correlation with MC. These findings suggest that the general extension messages may lack adequate postharvest handling information. The findings indicate that female ownership of bean grains may result in

a 1% decrease in MC compared to male farmers. Storage practices such as placing bags above ground and on cemented floors have a significant effect in reducing MC of bean grains (p < 0.05). Specifically, storing beans in bags placed above ground can contribute to a reduction in MC of up to 1.5%, while storing beans in bags on dry cemented floor can reduce MC by approximately 1.0%. The influence of farmer factors and grain size is negligible in this context.

Figure 6 illustrates that if more farmers were to adopt the traditional practice of storing beans in bags raised above the floor surface, the percentage of farmers who are likely to meet the recommended MC of ≤ 13.0 would increase from 26 to 47%. Moreover, the average MC for farmers using this practice would be 12.5% at an average storage duration of 91 days. This improvement in storage practice could contribute to enhancing food safety by ensuring that beans available to consumers meet the recommended MC levels.

Discussions

Farmer adoption of harvest and postharvest practices

The results show that many farmers still use traditional harvest and postharvest practices, with a significant number of farmers delaying harvest and threshing. Only a small percentage (< 10%) of farmers had a proper storage facility, with most opting to store their beans in bags on the floor or on a raised platform. These practices are typical of smallholder production systems in developing countries, where resource-constrained farmers find it difficult to adopt better harvest and postharvest handling practices, leading to poor postharvest outcomes, including high MC and food losses [17, 35, 48–51]. Addressing the limitations such as resource constraints that impede technology adoption among smallholder producers is crucial in encouraging them to adopt better practices.

Mass and value losses

The study findings revealed that inappropriate harvest and postharvest handling practices primarily at the farmer level, led to significant grain losses. These losses align with previous research [17, 24, 52], and the losses account for a net reduction of about 22% of total farmer bean produce, which implies a reduction in household income, producer output, and consumer surplus, and negatively impacting on household food security. The cost of postharvest losses represented over 86% of the total cost of postharvest handling activities. In other words, reducing postharvest losses can significantly lower the cost per unit and increase margins for smallholder farmers. However, if losses are too high, smallholder farmers may become uncompetitive in the output

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market, which could discourage investment in production and adoption of appropriate postharvest handling technologies including storage facilities. Thus, postharvest losses, as reported in this study, have the potential to offset the gains from adopting productivity-enhancing technologies [24].

Postharvest handling incurs the highest costs during harvesting and threshing, which are also the stages where the most significant postharvest losses occur. These activities require substantial labour and must be executed quickly, increasing the probability of losses due to the involvement of multiple workers or significant time. On the other hand, the stages of bagging and dressing exhibit the lowest postharvest cost, corresponding to minimal postharvest losses. The findings of this study align with the typical physical/manual primary processing activities [24]. As an example, smallholder farmers usually perform manual threshing during primary processing, and reducing losses during harvest and threshing would save value that could be utilized for other farm expenditure such as harvesting and threshing. It is crucial to enhance the efficiency of harvesting and threshing to reduce postharvest losses. Román et al. [53], modifying local practices has the potential to significantly decrease associated farmer production losses. Therefore, supporting smallholder farmers with appropriate postharvest handling technologies is essentially key in enhancing the efficiency of manual operations, starting with the stages that experience high losses, namely harvesting, threshing, and sorting.

Grain moisture content and storage practice

Results of this study showed that only 26% of farmers had beans with the desired MC level of ≤13%. This implies that a considerable percentage of beans stored by farmers do not meet the quality standards required by discerning buyers (at least by MC parameter), and this has implications for food safety as well as overall food and nutrition security. Farmer practices have the potential to cause total loss and worsen the safety of produce secured after harvest and primary processing. Moreover, a small change in grain MC can have a significant impact on storage duration. In this study, the practice of delayed harvesting was observed to either increase MC of dry beans, especially under weather conditions with high relative humidity (≥70%), which increases the risk of mold infestation, or decrease MC in a situation of low relative humidity. According to FAO [54], if it takes more than 10 to 15 days to reduce MC of grain to below 18%, mold may develop, be it in the field or in a store. Therefore, since some farmers delayed harvesting for up to 14 days, this may be a reason for the high grain MC for most farmers. The regression results revealed that beans harvested

after ≥ 7 days had a negative correlation with MC. Timely harvesting is critical in ensuring that bean grains have the correct MC, and potential losses are limited [10]. Thus, it is essential for farmers to always adhere to timely harvesting of mature dry beans to maintain good quality and reduce produce loss.

According to Ellis, Kwofie, and Ngadi [55], early harvesting of dry beans at physiological maturity is linked to mold development, while delayed harvesting is linked to high levels of postharvest losses. This observation has implications for farmers' prioritization of farm activities [24]. Despite this, farmers often view the timing of harvest as a minor aspect in grain losses [55], when in fact, prioritizing the harvest of bean grain at morphological maturity is crucial to reducing postharvest losses. The dry bean harvest period typically coincides with many other farm activities that must be performed simultaneously, and farmers also grow several seasonal crops that tend to mature at the same time. With ripe dry beans in the garden, farmers may prioritize other farm activities, leaving the morphologically mature beans in the garden for some time. It is also noteworthy that the harvesting periods for the first cropping season tend to coincide with the rainy season (Aug-Nov, Fig. 2), and at the morphological maturity stage, grain in pods is not protected from rainwater, putting it at risk of being harvested with high MC and presenting a risk of developing mold that reduce grain quality and later compromise food safety. Our study also found that when women were solely responsible and in full control for the beans, there was a higher chance of achieving the desired MC. This result supports our previous analysis which showed that a greater proportion of women (31%) compared to men (23%) had beans meeting the required MC level (≤ 13%). This is also consistent with findings from Shee et al. [37], who reported that postharvest losses tend to be lower among female farmers. This finding underscores the importance of women's involvement in postharvest handling. In many smallholder farming operations, women typically carry out labour-intensive tasks such as sorting, winnowing, postharvest storage, and grain drying [24, 56]. In a study on store hygiene, Makinya et al. [57] also found that female store owners had lower postharvest losses than male store owners. As a result, gender has implications on the outcomes of grain management, with women in charge, it is more likely possible to achieve better drying and have the desired levels of grain MC.

Grains with high MC are prone to pest infestations and can lead to economic losses due to grain rotting and mold development [6, 58]. Although storage practices had the potential to reduce grain MC, the reduction was not sufficient to meet the recommended level. Farmers who

stored grain in bags raised above the floor surface had grain 1.3% above the recommended level after 38 days of storage. Whereas storage in bags placed on tarpaulins showed the lowest MC, it was still 0.4% above 13.0% at an average storage duration of 56 days. Bakhtavar et al. [60] showed that different storage bags lead to different MC levels after a period of storage. More airtight storage facilities usually result into lower MC as opposed to less airtight facilities. The inability of the storage facilities and practices (adopted by farmers) to maintain stable relative humidity as storage duration progressed contributed to the high grain MC. Majority of smallholder farmers did not have proper storage structures and often stored produce in rooms with inappropriate ventilation, which further exacerbated the problem. Grain MC depends on the ability of a storage facility/ practice to maintain stability of low humidity, within the grains, relative to the atmospheric humidity. Control of humidity in a non-storage-purpose structure was not tenable. Poor grain storage structures used by smallholder farmers coupled with high humidity in a tropical environment can potentially lead to high levels of postharvest losses [59]. It appears that factors such as storage duration and practice have a greater influence on grain MC than the storage facility itself. Proper drying and adoption of alternative postharvest handling practices that can maintain grain MC at the required level is key in minimizing potential postharvest losses and income losses.

While access to information is crucial in encouraging the adoption of appropriate technologies such as postharvest and storage techniques [61], this study found that access to general bean production information did not necessarily result in lower grain MC among farmers. Only 20% of the farmers surveyed received information on bean production, and a mere 1% had ever received information on post-harvest handling. The provision of information has been shown to accelerate technology adoption [51], but this study's results contradict that notion and raise questions about the type, relevance, and sufficiency of information often supplied by various agents. The finding implies that the information farmers received was not useful for post-harvest handling aspects. Thus, providing relevant extension information becomes critical in helping farmers maintain grain quality during storage. According to Owach et al. [48], supplying farmers with beneficial post-harvest handling information is necessary, to ensure they meet the required grain standards.

Storage duration and moisture content

Farmers often store beans to ensure food security and take advantage of price premiums at a later time of selling. However, findings from the study reveal that a considerable percentage of farmers had beans with a MC above 13.0%. Similarly, many farmers did not sort or treat their dry grains, despite these activities being relevant in improving the quality of dry beans delivered to the market in addition to having an impact on price and crop income. As crop prices are usually highest at mid to near end of a cropping season and lowest at the peak of the crop harvest [24], storage of dry grain becomes crucial in ensuring farmers sell their produce when prices are competitive. As a result, many farmers store part or all their harvest for later sales to reap price premiums. In this case, over 78% of the surveyed farmers had dry bean grains in storage, with 48% of them having stored them for an average of 30 days. However, storing grain may present a risk in terms of qualitative and quantitative losses, depending on the post-harvest handling and storage practices. Deterioration in quality due to pest infestation and in-store rotting associated with high MC [6, 58], can potentially undermine anticipated price premiums. Maintaining the right grain MC ($\leq 13\%$) during storage can avert the risk of qualitative loss due to moisture [60, 62]. Therefore, reducing storage losses, in addition to increasing the surplus available for sale, becomes essential to enhancing farm profits.

The duration of storage has significant implication on grain MC due to variations in weather conditions. This study highlights the relationship between different storage practices, storage duration, and grain MC under farmer conditions. Although farmers adopt different storage practices, the applicability and relevance of these practices to reduction or maintainance of MC to the required level are also influenced by the storage duration. Better storage practices enable farmers to store grains for an extended period [63]. This is crucial for sustained storage of dry beans in good condition. To achieve and maintain the desired MC level of $\leq 13\%$ during storage, it is essential that the adopted storage practice is effective for the desired storage duration. However, the practices adopted by farmers often make it difficult to achieve and maintain the desired MC level. Traditional storage facilities and practices are associated with higher post-harvest losses due to the failure to maintain appropriate MC during storage [19]. Poor storage practices are also linked with shorter storage duration, making it hard to take

advantage of price premiums later in the season. In this study, grain storage on a raised platform, usually in plastic gunny bags placed on pallets, showed the potential to store for over 60 days. On the other hand, storage on the floor was detrimental to grain quality if stored for more than 60 days. In general, farmer storage practices have a strong implication on storage duration, which determines whether a farmer receives the anticipated price premium and better bottom-line margins for deferred sales.

Conclusions

Dry bean grain losses and their value were assessed during harvest and postharvest handling. The results show that farmers face significant losses due to poor handling practices, with up to 22% of the grain lost and valued at US$ 103 per hectare or 17% of farmer output. The adoption of appropriate practices is low, and traditional methods are associated with high MC (15%) during storage. Only 26% of farmers had beans meeting the desired moisture level. Storing beans in bags above the ground increased storage duration and had a likelihood of reducing MC by additional 1.5%, with a potential of almost doubling the number of farmers meeting the desired moisture level. These findings highlight the need to improve postharvest practices to reduce losses,

improve grain quality, enhance income, and contribute food safety. This can ultimately improve overall food and nutrition security. The evidence suggests that inappropriate harvest and postharvest practices lead to high losses and high MC of bean grains above the standard of $\leq 13.0\%$, rendering 74% of the bean grain of less desirable quality. This is a cost on farmer income and undermines efforts to combat poverty, food insecurity, and food safety. To minimize losses, farmers need to adopt appropriate and cost-effective postharvest handling technologies, especially for harvesting, primary processing, and grain storage. Interventions that focus on postharvest handling stages with the highest losses, including storage, need to be adopted to avoid income losses and contribute to reducing food losses and improving food safety. The findings highlight the need for interventions to build farmer capacity in postharvest handling practices and access to appropriate technologies.

Appendix

See Tables 13, 14, 15, 16 and 17.

Table 13 Study Sites

Region	District	Sample	Sample size (%)
Central	Nakaseke	94	21.1
Eastern	Sironko	92	20.7
Western	Hoima	93	20.1
Northern	Arua	88	19.8
	Oyam	78	17.5
Totals	05	445	100

The data was collected from 445 farmers selected from five districts in Uganda with closely equal proportional sub samples across the districts. Source: Field study, 2019

Table 14 Farmer and household variables

Explanatory variable	Variable description	Percent of respondents (*N* = 445)
Female farmers	Dummy: 1 = Male, 0 = Female	44.7
Household (HH) head	Dummy: 1 = Yes, 0 = No	71.2
Male headed household	Dummy: 1 = Male, 0 = Female	81.4
Marital status	Categorical variable	
	1 = Never married	2.9
	2 = Married	81.8
	3 = Separated	15.3
Education level of HH head	Categorical variable	
	1 = Primary school	58.7
	2 = Secondary school	30.3
	3 = Vocational training	5.6
	4 = University	2.2
	5 = No formal education	3.2
Main occupation	Categorical variable	
	1 = Crop farming	64.3
	2 = Mixed farming	24.3
	3 = Formal/salaried employment	4.5
	4 = Casual worker	2.7
	5 = Small business	3.6
	6 = Religious service	0.7
Household type	Categorical variable	
	1 = Dual household type	46.8
	2 = Female decision maker	16.6
	3 = Male decision maker	36.6

Source: Field study, 2019

Table 15 Key postharvest challenges and constraints

Variable	Percent	Obs
Labour constraints	4.0	18
Access to materials/equipment	3.2	14
Lack storage facilities	7.6	34
Excess rains	22.9	102
Financial constraints	4.7	21
Lack drying facilities	4.7	21
Storage pests	30.1	134
Mould	1.8	8
Loss of quality (discoloration)	1.4	6
None	13.0	58
Other	6.5	28

Source: Field study, 2019

Table 16 Quantity lost per stage (Kg/ha)

Variable	Mean (N = 1335)	Std. Dev	Min	Max
Harvesting	37.35	60.86	0.00	625.37
Drying pods	12.87	21.34	0.00	176.50
Threshing	32.05	31.18	0.31	261.70
Winnowing	15.46	24.59	0.14	249.53
Sorting	31.83	31.36	0.00	261.70
Treatment	2.39	8.79	0.04	172.97
Bagging	2.28	4.6	0.05	58.83
Storing	30.94	31.14	0.31	261.70
Drying grain	7.68	15.11	0.04	152.53
Secondary processing	0.00	0.00	0.00	0.00
Other	0.91	1.87	0.02	26.86
Transporting	8.33	16.14	0.10	129.43
Re-bagging	2.83	6.34	0.00	147.91
Amount lost (Kg/ha)	184.34	171.09	3.32	1480.45

Source: Field study, 2019

Table 17 Comparison of model goodness of fit

Regression	F stat./Wald chi2	R^2	AIC	BIC
ols	6.35 (0.0000)	0.0523	− 3833.811	− 3790.304
glm	–	–	− 2.764	− 6260.559
betareg	49.08 (0.0000)	–	− 3863.573	− 3810.434
betafit	48.74 (0.0000)	–	− 3862.855	− 3809.716
betamix	46.90 (0.0000)	–	− 3862.855	− 3809.716
betamix (adjusted—UNOBS)	111.85 (0.0000)	–	− 3796.256	− 3699.638
betamix (adjusted + UNOBS)	116.18 (0.0000)	–	− 3794.714	− 3693.266

Values in parenthesis are p values. Source: Regression Output

Availability of data and materials
Availability of data and material anonymized data is available upon request from the corresponding author.

Declarations

Consent for publication
Consent was obtained from all individual participants who supplied information used in the study.

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

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