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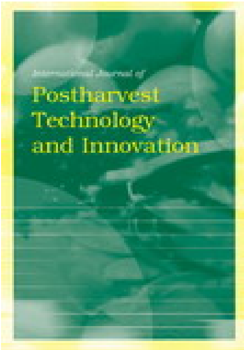

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Birhanu Atomsa Gurracho, Yetenayet Bekele Tola, Abebe Fanta Badie, Solomon Abera Habtegabriel, Sirawdink Fikreyesus Forsido

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Assessment of on-farm sorghum grain loss under farmers' traditional postharvest practices in the East Hararghe Lowlands of Ethiopia

Birhanu Atomsa Gurracho*

Department of Agricultural Engineering,
Fadis Agricultural Research Center,
Oromia Agricultural Research Institute,
Harar, Ethiopia
Email: biratomsa22@yahoo.com
*Corresponding author

Yetenayet Bekele Tola

Department of Postharvest Management,
College of Agriculture and Veterinary Medicine,
Jimma University,
Jimma, Ethiopia
Email: yetenayet@gmail.com

Abebe Fanta Badie

Department of Agricultural Engineering,
Haramaya Institute of Technology,
Haramaya University,
Haramaya, Ethiopia
Email: aberasol22@gmail.com

Solomon Abera Habtegabriel

Department of Postharvest Technology,
Haramaya Institute of Technology,
Haramaya University,
Haramaya, Ethiopia
Email: aberasol22@gmail.com

Sirawdink Fikreyesus Forsido

Department of Postharvest Management,
College of Agriculture and Veterinary Medicine,
Jimma University,
Jimma, Ethiopia
Email: sirawdink@gmail.com

Abstract: Assessment of on-farm sorghum grain loss under farmers' traditional postharvest practices was conducted in East Hararghe Lowlands in Ethiopia to determine grain loss magnitudes at on-field operation stages. The study used split-plots design with three sorghum varieties and three harvesting times assigned to whole plots and sub-plots, respectively. Harvesting grain loss means were varied from 2.25% to 7.33% with harvesting time. The highest grain loss was recorded at threshing stage with significant differences among the varieties ranging from minimum of 4.40% for Makko to the maximum of 8.52% for Qaqqaba. The total on-farm loss increased from 15.44% for Makko to 18.89% for Malkam harvested at first and last time, respectively. Harvesting on 10 days after days to maturity indicated reduced total on-farm loss for all varieties. On-farm sorghum grain loss causes an estimate of $545.80 million loss to the country, annually.

Keywords: assessment; harvesting; on-farm loss; postharvest; sorghum grain; threshing; traditional practices; varieties; Ethiopia.

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Biographical notes: Birhanu Atomsa Gurracho is a senior researcher in Agricultural Engineering Department of Fadis Agricultural Research Centre in Oromia Regional State, Ethiopia. He has received his BSc in Agricultural Engineering and MSc in Post-Harvest Technology, both from Haramaya University, Ethiopia. Currently, he is PhD candidate in post-harvest science and technology at Jimma University, Ethiopia. His interest is in the research area of designing, development and evaluation of agricultural machines, focusing on increasing productivity, reducing loss, improving shelf life, value addition and preservation. He has published various articles in different local and international journals and in conference proceedings.

Yetenayet Bekele Tola is an Associate Professor in the Department of Post-Harvest Management at Jimma University. He obtained his BSc in Horticulture Science from Jimma University (Ethiopia), MSc in Food Technology specialising in Postharvest Technology (KU Leuven, Belgium), and PhD in Food Technology from McGill University, Canada. His research interests mainly focused on loss reduction, value addition, and food preservation. He has published more than 60 articles in peer-reviewed indexed journals and four book chapters from his research works.

Abebe Fanta Badie has received his BSc in Agricultural Engineering from Addis Ababa University, Ethiopia. He received his MSc and PhD in Agricultural Machinery Design from National College of Agriculture, and from School of Agriculture, Food and Environment, Cranfield University, Great Britain. He has been working for Haramaya University in Ethiopia and has experiences of over 46 years in teaching and research in agricultural machinery. He specialises in design of field machine, post-harvest machine design, soil dynamics in tillage and traction research, with keen interest in design, testing, performance evaluation, certification and registration of agricultural machinery.

Solomon Abera Habtegabriel is working for Haramaya University, Ethiopia as an instructor, teacher, and researcher, and served at different positions since 1985. He joined then Alemaya College of Agriculture, Addis Ababa University where he earned his BSc in Agricultural Engineering. He received his MEng Science in Agricultural Machinery from University College Dublin, Republic of Ireland. He attended the Asian Institute of Technology, Bangkok and awarded a DEng in Food Engineering and Postharvest Technology. His is interested in postharvest and food engineering research areas, majoring product processing, size reduction, drying, storage and food preservation.

Sirawdink Fikreyesus Forsido is an Associate Professor at the College of Agriculture and Veterinary Medicine, Jimma University, specialising in Food Science, Nutrition, and Postharvest Technology. With a keen interest in mitigating food loss and waste, his research delves into complementary foods and food product development. His extensive publication record includes studies on postharvest loss and the effects of processing on nutritional and functional properties. He actively contributes to ongoing research, supervising PhD dissertations and MSc theses while participating in international conferences. His dedication to advancing food science is evident through his diverse academic pursuits and collaborative efforts.

1 Introduction

Sorghum [*Sorghum bicolour* (L. Moench)] is the fifth most important grain crop on the globe and a dietary staple for more than 500 million people in semiarid tropics, mainly in Africa and Asia (Lindsay, 2010). Ethiopia is among the largest sorghum-producing countries in the world, ranking third in Africa and sixth globally (Charles et al., 2009; Hari et al., 2017). According to different sources, more than 4.8 million metric tons of sorghum is annually produced in Ethiopia from approximately 1.80 million hectares (Solomon et al., 2018; CSA, 2020, 2021). Sorghum production represents 17.74% of the total cereal production and 17.45% of the total land under cereals in Ethiopia, engaging more than 5 million Ethiopian farm holders (CSA, 2018).

Hararghe part of the Eastern Oromia national state represent the sorghum production belt that contributes the largest production ratio in Ethiopia. In the East Hararghe zone, sorghum occupies 39.08% of the total crop cultivated lands and 65.21% of land under cereal production and approximately shares 65% of the zone total cereal grains production (CSA, 2020). The annual total sorghum production of the zone was approximately 0.52 million tons, with an average yield of 2.9 ton/ha, as indicated in the report.

There are different types of sorghum varieties released by research institutions and produced by farmers in Ethiopia in general and Haraghe areas in particular. Many of these varieties are currently in production within different districts of the West and East Haraghe zones, mainly in moisture-stressed environments of lowlands areas. Most of these improved lowland varieties have been preferred by the farmers for their better and production potential under low moisture conditions. However, it was observed that the existing postproduction practices cause high postproduction loss as the released varieties are prone to different loss factors after maturity that contributes to the reduction of food grain supply to the market or farming family income according to the Ethiopian Ministry of Agriculture. The higher after-harvest loss was not only associated with the nature of varieties but also linked with traditional on-farm practices. However, scientific information from field-based study reports to identify major causes, critical loss points and estimates of on-farm grain loss is scarce. Furthermore, there is wide variation in the estimates of the extent of the losses. According to the Hodges et al. (2014), there are various figures quoted by different authors for grain loss in Ethiopia, but they lack clarity on the measurement methods used to estimate losses, fail to indicate the original information sources, and fail to indicate losses at the different stages of the postproduction operation. Hengsdijk and Conijn (2014) and Hengsdijk and de Boer (2017) further indicated the importance of accurately determining quantitative and qualitative losses at the field level, saying that former studies mainly focused on storage losses.

The lack of reliable information on magnitude of grain loss after production and the scarcity of loss data generated through a quantitative study approach indicate the need for detailed investigations to generate data on the magnitude of on-farm postproduction sorghum grain loss under the traditional methods practiced by farmers in Ethiopia in general and, particularly in East Hararge lowland areas. Information generated from this study will help to develop grain loss reduction mechanisms at different stages of the on-farm postproduction operation chain. Therefore, this study aimed to determine the magnitude of on-farm grain loss during harvesting time and other on-field postharvest operations for different varieties at different harvesting intervals after DM, and to identify the stage of critical grain loss point under traditional practices of the farmers in East Hararghe lowland areas of Ethiopia using three early maturing sorghum varieties.

2 Materials and methods

2.1 Description of the study area

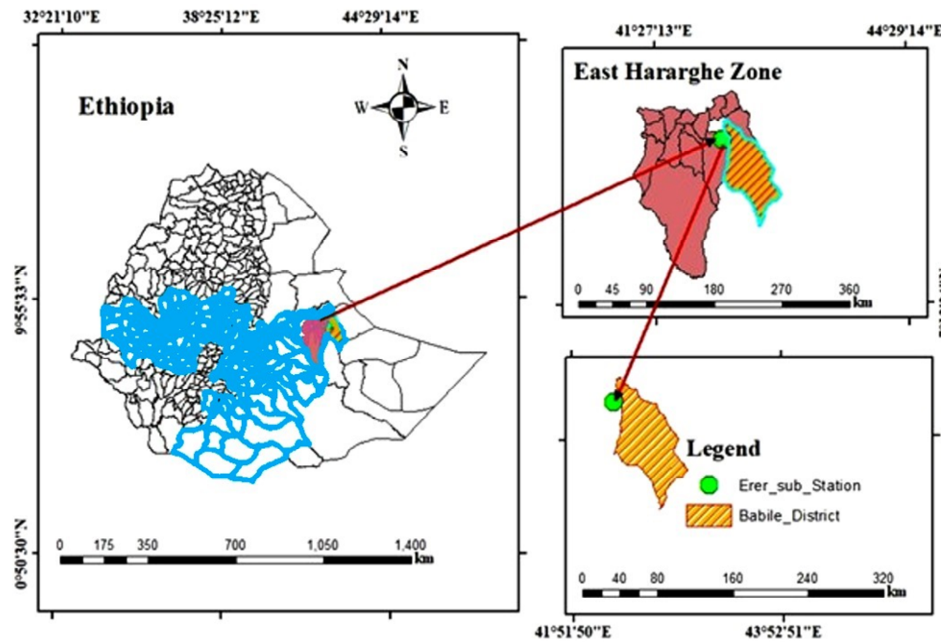
The study was conducted in the lowlands of East Hararghe zone in Eastern Ethiopia during the main growing season of the 2020/21. The zone is located on 7^0 32’ to $9^0$44’N and 41º12’ to 42º53’E, as indicated in Figure 1.

The East Hararghe zone receives annual mean rainfall of 400 to 1200 mm and has an agroecological distribution of 7.7% highlands, 24.5% midlands and 67.8% lowlands. The specific study site was the Fadis Agricultural Research Centre (FARC) substation located in the Erar valley of the Erar Ibada rural area under the Babbile district of the East Haraghe Zone. The Erar research sub-station of FARC is located at altitude of 1,130 to 1,240 m above asl and it is a site established to represent the wide mass of east Hararghe lowland areas. The study site receives annual rainfall of 450 to 650 mm, minimum and maximum annual relative humidity of 27.24% and 79.22%, and minimum and maximum mean temperatures of 14.93ºC and 31.2ºC.

2.2 Research materials

The sorghum varieties of *Makko, Qaqaba* and *Malkam* were selected among the improved varieties adopted by farmers of lowland areas. They are all white type and early maturing varieties of relatively similar properties. They were selected based on adoption level, preference of local farmers, potential yield and other similarities like, recommended production inputs, crop management, plant stands, and days to maturity (DM) with more variation in lodging and grain shattering as related to their drying behaviours after DM according to information gathered from agronomists and sorghum breeders of FARC. The DM for *Malkam*, *Makko* and *Qaqqaba* varieties are 119, 110 and 117 days, respectively (Fuad et al., 2017, 2018). A digital balance of 50 kg capacity (0.001 resolution) for measuring samples of large quantities like total harvested heads and grain outputs obtained per unit plots and analytical balance of 3000 g capacity with 0.001resolution used for small samples like collected losses and moisture content tests were among the laboratory instruments used. A digital Memmert brand Universal Oven was employed to determine grain moisture contents.

Figure 1 Geographical location of the Erar research site in East Haraghe Zone of Oromia Regional State in Ethiopia (see online version for colours)



2.3 Experimental design and treatment factors

The on-station field trial loss assessment method was applied with a load tracking approach according to the harvesting and postharvest loss measurement guidelines recommended by FAO, 2018). The experiment was consisted of two treatment factors with each of them entailed three levels arranged in 3x3 factorial treatments and laid out in split-plot design with 3 replications (Douglas, 2013). The two treatment factors of the study were sorghum crop with 3 level of the above listed different varieties and harvesting time factor with three different levels of harvesting time intervals considered after DM. The three levels of harvesting time were selected at difference of 10-days intervals starting from the second day after DM. The levels coded DM+2, DM+12 and DM+22 with the numbers indicating delays of harvesting time intervals after DM, relatively representing the early, medium and late harvesting time, respectively.

The entire range of harvesting period was selected within the actual range of sorghum harvesting time during majority of the farmers in the vicinity of the study area harvests their sorghum crops. The intervals of harvesting times were selected to determine the effect of different harvesting time intervals after DM on loss of grain sorghum during harvesting and other on-farm operations as well as variation of the effects on different sorghum varieties due to variation of the characteristics among the cultivars. Thus, variabilities among the varieties were differences of the treatment levels except DM that was managed by adjusting different planting dates so that they get matured together.

A field of more uniform condition but having a slight slope was selected and used with blocking method to minimise the variability. The three blocks were laid horizontally across the slope with each block comprised of three whole plots using two metres spaces between them. Each of the main plots were further divided into three sub-plots with 10 m × 10 m areas of each unit sub-plot leaving spaces of 1.5 metres between them. The treatments' levels were then randomised independently and separately according to the design selected. The three varieties as the levels of the main factor were assigned to the whole plots in a block in a complete randomised manner using lottery method. The three levels of the harvesting times were assigned to the sub-plots of a whole plot in a random order, using the same method.

Maximum efforts were made to make the production and management practices uniform except the objectively varied treatment levels. The same groups of personals were used throughout the field operation and the day was used to perform replication units at every operation stage. The personals involved were trained for accurate processing operations and measuring of the response parameters, and made aware of the potential introduction of systematic errors during the experiment

2.4 Grain loss variables and estimation of the loss values

Estimation of quantitative grain loss during field activities of post-production processes was started with determination of the produced grain available (potential yield) two days after DM. Data from these measurements served as a baseline information to determine extent of grain losses during delayed harvesting and subsequent on-farm postharvest practices. The chain of postproduction field activities was grouped in to five major stages as:

1 harvesting

2 on-field storage/stacking for drying

3 threshing

4 winnowing and cleaning

5 pre-storage handling (from bagging to time of arriving home level storage place).

The measurements and determination of the losses at each of the operation stages were performed following the recommended guidelines of FAO (2018) and others reports (FAO, 2017a; Global Strategy, 2017; Kebe, 2017) as described below.

1 *Determination of potential yield*: Potential yield is the total grain available on the mature heads of sorghum plants ready for harvest just at the end of DM with zero postharvest loss, which is an imaginary value of 100% harvest with no loss. The potential yield data is the base for estimation of the grain losses during the chain of post-production operation stages. The potential yield was measured by random sampling of a row from each of the unit plots of the study. Heads of sorghum plants

on every of sampled rows were carefully stripped into separate bags. The harvested samples distributed in large bags without overlap of heads were kept under the sun on raised platform until the moisture was reduced sufficiently. The samples were then, threshed, and cleaned manually and carefully with maximum efforts in such no grain loss existed. The weight of grain recorded from each sampled row multiplied by the number of rows in its respective unit plot was the estimate of potential yield (Y_P) available before start of the first harvesting for that specific plot. The same was repeated before the start of harvest for DM+12 and DM+22 days.

2 *Determination of grain loss during manual harvesting*: The common manual harvesting method practiced by the farmers is cutting heads by sickles from the standing plants. The loss of grins during strip harvesting comprises grains shattering from heads while cutting and placing heads on the ground. In this study, the plot ground under the standing plants was thoroughly cleaned from any weeds, plant leaves and grains fallen on the ground The heads were then stripped by the trained farmers. The stripped heads were then placed on plastic sheets laid between the plots. The harvested heads were then collected from plastic sheet in to bags and moved to the temporary storage place as practiced by farmers with the bags avoiding loss of grains on the way. Harvesting of unit plots in a block assigned to the same harvesting level were performed simultaneously to control error due to differences of air conditions in a day while similar levels from all blocks were harvested on the same day. After harvesting of a plot was completed, grains fallen on the plot ground and detached grains remained on the plastic sheet, including heads missed were thoroughly searched, collected, cleaned, dried, weighed and recorded to estimate grain losses during manual harvesting. The total harvesting grain loss percent from the potential yield was computed using equation (1).

$$H_{GL} = \frac{W_{HL}}{Y_P} \times 100, \quad (3)$$

H_{GL} = total grain loss during harvesting (%)

W_{HL} = weight of total grain loss during harvesting (kg)

Y_P = potential yield estimated (kg).

3 *Grain loss during temporary on-field storage*: The harvested produces of unit plots were weighed and stored separately in the field under ambient natural conditions that also being dried until threshing time is reached, as practiced by farmers. Weight loss of the harvested produce during temporary on-field storage and drying includes weight of moisture lost due to drying, weight loss due to grains consumed and damaged by rodents, insects and other pests, and weight of grains shattered at the storage place. The actual grain physical loss of the stage was estimated from the total dry weight differences of the harvested produce before and after storage using the initial and final moisture contents. The dry weight loss of the harvested produce during on-field storage was determined using equation (2) as:

$$D_{WL} = \left[W_{H1}(1 - M_1)\right] - \left[(W_{H2} + S_{FS})(1 - M_2)\right] \quad (2)$$

where

D_{WL} = dry weight loss of grain (kg)

W_{H1}= weight of the harvested produce before storage (kg)

M_1 = moisture content (wb) before storage (decimal)

W_{H2} = weight of the harvested produce after storage (kg)

S_{FS} = weight of shattered grains collected from storage place (kg)

M_2 = moisture content (wb) after storage or at threshing time (decimal).

The dry weight of grain loss was then adjusted to 14% grain moisture content for the actual value of the grains lost at marketing standard grain moisture (John, 2021). The total loss of field storage was the sum of grain collected from the storage ground and the dry weight loss at adjusted moisture, calculated using equation (3):

$$L_{FS} = \frac{W_{FSL}}{Y_P - W_{HL}} \times 100 \tag{3}$$

where

L_{FS} = loss from the harvested net grain entered on-field storage (%)

W_{FSL} = total grain loss during field storage (kg)

Y_P and W_{HL} as previously defined.

4 *Determination of grain-to-straw ratio*: Grain-to-straw ratio is a measure of grain content for the harvested produce. It is important base to estimate the total grain entering a threshing stage and to control the accuracy of grain loss data collected during threshing and cleaning. It is mainly important when the process causes significant grain damages in which the broken dusty particles blown away cannot be collected for measurement and affects the output data. The grain to straw ratio data is important control for the accuracy of threshing and cleaning output data as the sum of all losses and final grains output after threshing and cleaning should be equal to the grain in the harvested produce before entering threshing system. Random samples of 2 to 3 kg taken in 5 replicates per unit plot of harvested produce were used to determine the grain to straw ratio. The samples were threshed manually and carefully and the resulted weight of clean grain in a samples was registered as W_n corresponding to each of the n^{th} samples. The mean grain content of the harvested produce and grain to straw ratio were calculated from the sample results with equations (4) and (5), respectively.

$$G_C = \frac{1}{N} \sum \left(\frac{W_n}{S_n} \right), \tag{4}$$

$$G_{SR} = \frac{G_C}{1 - G_C} \tag{5}$$

where

G_C = average grain content of the harvested heads (decimal)

W_n = weight of clean grain obtained from the 'n^{th}' sample (kg)

S_n = weight of the 'n^{th}' sample before threshing (kg)

N = total number of samples taken per plot

G_{SR} = grain to straw ratio (no unit).

5 *Grain loss during threshing*: The threshing operation was performed by beating the harvested sorghum heads spread on the ground covered by a wide plastic sheet, using sticks as practiced by farmers. Grains scattered around threshing field and grains discarded mixed with in straws after being detached from the ears were thoroughly collected for scattering loss. Unthreshed grains remained on the exhausted straws discarded by decision of the operating farmers were collected by finger picking from the straws and weighed as unthreshed grain loss. Damaged loss of grains was determined by taking samples of the threshed grain output in three replicates and sorting mechanically damaged grains and grains with any visible crack or fracture from the samples. The total threshing loss of grains was calculated from the sum of scattered grains, unthreshed grains and mechanically damaged grains. The percent of loss from grains entered threshing and from potential yield were calculated by equations (6) and (7), respectively.

$$T_{LN} = \frac{W_{TL}}{Y_{NT}} \times 100 \qquad (6)$$

$$T_{Lp} = \frac{W_{TL}}{Y_P} \times 100 \qquad (7)$$

where

T_{LN} = threshing grain loss from the net grain entered threshing stage (%)

W_{TL} = total grain loss during threshing (kg)

Y_{NT} = Net gain entered the threshing (kg)

T_{LP} = threshing grain loss from potential yield (%)

Y_P = potential yield (kg).

6 *Determination of grain loss during cleaning*: Cleaning loss consists of grains blown with chaffs and/or scattered away out of the intended cleaning area during winnowing as well as grain discarded and spillages during cleaning from heavier impurities. The grains obtained at all the mentioned loss positions were thoroughly collected by hands, weighed and recorded for winnowing/cleaning loss. The total percent of grain loss during cleaning was computed with equations (8) and (9), respectively from total grain entered cleaning stage and from the potential yield as indicated below.

$$C_{LN} = \frac{W_{CL}}{Y_{NT} - W_{TL}} \times 100 \qquad (8)$$

$$C_{LP} = \frac{W_{CL}}{Y_P} \times 100 \quad (9)$$

where

C_{LN} = loss from total grain entered cleaning stage (%)

C_{LP} = loss from the potential yield (%)

W_{CL} = the sum of all collected cleaning grain losses (kg)

Y_{NT}, W_{TL} and Y_P as defined above.

7 *Pre-storage handling grain loss*: Grain loss at this stage is a collection of different losses. It includes grains collected from spillages while filling in to bags, spillage through holes on bags during weighing and packing. The losses during loading, transporting and unloading were determined by difference of weights recorded before loading and after unloading at home level. The sum of these losses was used to compute the total percentage grain loss of this stage on the bases of net grain after cleaning and the potential yield using equations (10) and (11), respectively.

$$L_{BT} = \frac{W_{BT}}{W_{CG}} \times 100 \quad (10)$$

$$P_{BT} = \frac{W_{BT}}{Y_P} \times 100 \quad (11)$$

where

L_{BT} = grain loss during bagging from cleaned product (%)

W_{BT} = total grain loss during bagging and transport (kg)

W_{CG} = net grain obtained after cleaning (kg)

P_{BT} = bagging and transport loss from potential yield (%).

8 *Total on-farm postproduction loss of grain sorghum*: The total on-farm postproduction loss is the cumulative weight losses at all stages from harvesting until transporting the product to home storage. The total loss was calculated using equations (12) and (13) as indicated below.

$$W_{PPL} = \left(W_{HL} + W_{FSL} + W_{TL} + W_{CL} + W_{BT}\right) \quad (12)$$

$$T_{PPL} = \frac{W_{PPL}}{Y_P} \times 100 \quad (13)$$

where

W_{PPL} = sum of postproduction loss (PPL at all stages, kg)

T_{PPL} = total on-farm postproduction loss (PPL) from potential yield (%)

others as originally defined.

9 *Loss during intervals between harvesting levels:* This loss was the difference between the initial potential yield recoded before the start of harvesting and the total yield obtained at each of the latter harvesting times. This difference was considered mainly due to grains shattered eaten by birds and pests during the days of intervals between levels of harvesting times and it was calculated by equations (14) and (15) as below.

$$Y_D = Y_P - Y_H \tag{14}$$

$$L_B = \frac{Y_D}{Y_P} \times 100 \tag{15}$$

where

Y_D = The difference between Y_P and Y_H (kg)

Y_H = sum of all grains obtained from harvested produce of each unit plot including all losses (kg)

L_B = loss of grain from unharvested plots during days of intervals between harvesting times (%)

Y_P as defined originally.

10 *Moisture content consideration*: The moisture contents of sorghum produce (grains and head straws) were measured at every stage of the investigated operation process using the oven dry method. The difference in grain moisture content was considered for the accuracy of the actual grain loss. All the recorded grain weights were adjusted to the grain weight of 14% (wb) recommended for sorghum grain at storage and marketing (Brent, 2018; John, 2021).

2.5 Economics of on-farm sorghum grain loss

Economic loss generally denotes a reduction in the monetary value of a product as a result of physical loss, reduction in weight, qualitative loss, nutritional loss and/or germinative loss due to different causes (Ayo et al., 2017; Vishwakarma et al., 2020). The economic analysis in this study was based on the physical loss of sorghum grain during the chain of on-farm operation stages after production. The monetary value of the loss was computed based on the market price of sorghum grain at the time of this study. The economic loss in this study was stated in $USD using the exchange rate of the National Bank at that time. The economic loss was estimated for individual farmer loss per hectare and at the country-wide annual production scale. Loss economic values at the farm and at national levels were calculated using equations (17) and (18), respectively, as indicated in Klara et al. (2022) and Teferra (2022).

$$F_{EL} = M_P \frac{(P_L . Y_P)}{100} \tag{16}$$

$$N_{EL} = M_P \frac{(P_L . A_P)}{100} \tag{17}$$

where

F_{EL} = farmer economic loss per hectare (\$USD)

Y_P = mean yield recorded in this study (ton/ha)

N_{EL} = annual loss for the country (\$USD)

M_P = average marketing price of sorghum (\$USD/ton)

P_L = average on-farm postproduction loss of sorghum (%)

A_P = annual sorghum production of the country (ton).

The sorghum price data was collected for the period of November 2021 to March 2022 from markets nearer to the study area indicated range of 2900 to 4500 Birr per 100kg. The wholesale price reported for various locations of the country by different organisation during the same period were also taken into account to estimate the average price at country level. The Ethiopian Statistics Service (ESS) (2022) monthly consumer price index for different locations, the FAO (2021) monthly report on food price trends indicated for Ethiopia, the USDA (2022) annual assessment report in Ethiopia and USAID (2022) sorghum grain wholesale prices report for various locations in Ethiopia for 2021/22 were among the additional information used to estimate the annual average sorghum price in Ethiopia. The annual on-farm postproduction sorghum grain loss of the country was calculated from the annual production of the last four years (2017/18 to 2020/21) reported officially (CSA, 2018, 2020, 2021).

2.6 Data analysis

The experimental set up had 3 replication blocks, 3 main plots in a block, and 3 sub-plots per main plot giving a total of 3x3x3 =27 observations. The collected data were organised according to the experimental design used and subjected to statistical analysis using Genstat 18th edition computer software. Analysis of Variance (ANOVA) method was used and no data transformations were made as ANOVA assumptions were met for all the variable parameters. Ryan/Einot-Gabriel/Welsch (REGW) multiple comparison test was used to determine significance of the means differences using the least significance difference (LSD) at 95% confidence interval.

3 Results and discussion

3.1 Loss during harvesting

The harvesting loss of grain indicated significantly different means (P<.01) for variations in each of the treatments' levels and for their interactions. Increasing mean grain loss was recorded with increase in intervals of harvesting time that showed grand mean of 4.60± 1.63% for all varieties. The means ranged between a minimum of 2.35± 0.16% for *Qaqqaba* variety at the early-stage harvesting (DM+2) and a maximum of 7.33± 0.49% for *Malkam* at the final harvesting stage (DM+22), as indicated in Table 1.

Table 1 Means of sorghum grain loss during traditional harvesting practices for different sorghum varieties and intervals of harvesting time from the total yield

Sorghum variety (DM)	*Means of harvesting grain loss (%) at different harvesting time*		
	Early harvest (DM+2)	*Intermediate (DM+12)*	*Last harvest (DM+22)*
Makko (110)	4.15 ± 0.28^{C}	4.66 ± 0.31^{CD}	7.32 ± 0.49^{E}
Qaqqaba (119)	2.35 ± 0.16^{A}	3.20 ± 0.22^{B}	5.04 ± 034^{D}
Malkam (117)	2.85 ± 0.19^{AB}	4.46 ± 0.30^{CD}	7.33 ± 0.49^{E}

Notes: Values = Mean ± SD; DM = days to maturity; superscript letter(s) in the table show significance of the differences; means with common letter(s) in superscripts have no significant difference.

The means of harvesting grain loss indicated an average rate of 32.05% increment between the first and the second harvesting, 59.22% between the second to the third harvesting time and a total of 110.26% average grain loss increment between the first and the last harvest produce. An increase in loss with an increase in the delay might be associated with an increase in shattering loss due to rapid drying linked with high evapotranspiration rate. The sunny days and high temperature during harvesting time could contributed for moisture loss of sorghum spikes results in an increase in shattering loss. The rapid moisture reduction from the mature sorghum caused shrinks in the stalks leading to lodging with delaying of harvesting time. This condition contributed not only for additional grain loss, but also increased harvesting labour and time.

The contribution of loss due to missed heads during manual harvesting was very low and less than 7% of the total harvesting loss. Thus, harvesting loss was largely caused by shattering of grains, that contributed 93.33% of the grand mean loss recorded. Grain shattering contributed 96%, 94% and 92% of the total harvesting loss in *Makko, Malkam* and *Qaqqaba*, respectively. This implies that *Makko* was more prone to shattering during harvesting, followed by *Malkam* and *Qaqqaba*. The time of harvesting, variety, crop moisture content and lodging were obtained playing major roles in harvesting loss of grain and this in agreement with Sattar et al. (2015) and Melese et al. (2022).

The result is lower than the average harvesting-related loss of 8.72% reported for three sorghum growing districts of Darashe, Alamata, Fadis and Lay Armachew in Ethiopia (FAO, 2017b). This difference may be due to the difference in the study approach in that the current study used actual measurements while the previous report used survey study results based on farmers' responses. Moreover, sorghum grain loss ranging from 8.7 to 16.3% was reported for combine harvesting by Michael (2003), depending on crop moisture at harvesting. However, the magnitude of the mean harvesting grain loss recorded at the third harvesting level disagrees with the maximum acceptable harvesting grain loss of 5% for efficient method (Brent, 2018).

In general, all varieties showed an increase in harvesting loss when the harvesting time was delayed by 12 and 22 days after calendar of DM. In particular, the last harvesting time (DM+22) caused significant harvesting loss in all varieties that ranged between 5.0 and 7.3%. The time length of keeping the crop unharvested after physiological maturity is very important for the reason that both early- and late-harvesting have significant effect on quantitative and qualitative loss of sorghum production (Oyier et al., 2017; Martins et al., 2024) though this information for optimum was, generally absent. This result implies that harvesting can be considered one of the critical loss points in sorghum and better to limit harvesting time below 12 days after DM.

3.2 Grain loss during on-field storage

The study of grain loss during on-field storage for 30 days showed significant difference ($P<0.05$) for harvesting time, but no significance difference among varieties and interaction of the two factors. On field storage or on field drying loss decreased with delay of harvesting time. The average losses were 2.55±0.49% at DM+2, 1.68±0.36% at DM+12 and 1.23±0.21% at DM+22 for which the grand mean was 1.82%. The decrease might be associated with grains shattering from late harvesting already exhausted at time of harvesting as compared to the early harvesting. On-field loss of this study for all varieties is higher than values reported by FAO (2017b), which were 0.63% from Fadis and 0.94% from Darashe. This deviation might be associated with the farmers self-reported estimation of the field storage loss than actual measurement. Furthermore, other factors like variety, field storage and weather condition during drying might contribute for the difference. As compared to harvesting related losses, on-field drying / storage loss has less significant impact. This loss was below 2% with less impact on food and economic security and not recommended to consider it as a critical loss point for intervention purpose. However, farmers can take extra efforts to reduce on field drying or storage loss for additional kilograms of grains to be saved.

3.3 Loss during threshing

Data from threshing grain loss showed high association with the traditional threshing practice of the farmers in sorghum. The result indicated significant ($p<0.01$) mean differences for variation of the factors levels and for the interactions between levels of factors (Table 2).

Table 2 Means of sorghum grain loss of traditional threshing practices as affected by varieties and harvesting time intervals from the total grain yield

Sorghum variety (DM)	*Mean loss for different varieties and different harvesting time*		
	Early harvest (DM+2)	*Intermediate (DM+12)*	*Last harvest (DM+22)*
Makko (110)	4.43 ± 0.41^{A}	4.41 ± 0.47^{A}	4.65 ± 0.47^{A}
Qaqqaba (119)	8.00 ± 0.79^{E}	7.32 ± 0.71^{D}	7.20 ± 0.70^{D}
Malkam (117)	6.01 ± 0.57^{C}	5.78 ± 0.54^{B}	5.40 ± 0.41^{B}

Notes: Values = Mean ± SD; DM = days to maturity; superscript letter(s) in the table show significance of the differences; means with common letter(s) in superscripts have no significant difference.

The threshing loss of grain from the total production showed grand mean of 5.91% with decreasing means from the maximum of 8.00±0.79% for the first harvested produce of *Qaqqaba* variety to the minimum of 4.41±0.47% in *Makko* variety harvested at the second harvesting interval, while the grand mean from the net grain entered the threshing level was 6.31%. The mean loss was varied with variation of the varieties. The threshing loss was larger for first harvest and then decreased for the later harvested produces from 6.11% to 5.79% on an average. Qaqqaba variety depicted the highest threshing loss at all harvesting time intervals while Makko indicated the lowest without significant variation between means losses of different harvesting time. The variation among the varieties could be due to differences in threshablity of varieties that depends on inherent properties of the individual variety and those properties might have also been affected differently in relation to drying under the high temperature of lowland environment.

The result obtained is within the threshing loss range of 5% to 9% reported for cereals by Tadesse and Regassa (2013). The average of the loss was also closer to threshing loss of 6.20% indicated by Mohammed and Tadesse (2018) in the summary of loss review paper. Measured threshing losses of 6.5% and 6% surveyed threshing loss of cereals in Ethiopia were also reported by Hodges et al. (2014). Grain loss of 8.46% reported for manual threshing also matched with this study result (Amponsah et al., 2017). A similar finding of 7.7% threshing grain loss for manual threshing method of *Teff* grain in Ethiopia was reported (FAO, 2016).

Scattered and separation grain contributed the highest percentage of the threshing loss, which shared 73.92%, 69.81% and 48.48% of the average threshing loss in the *Makko*, *Malkam* and *Qaqqaba* varieties, respectively. The contribution of unthreshed grain loss was higher in *Qaqqaba,* where it shared 51.52% of the average threshing loss, followed by Malkam, in which it contributed 27.92% of the stage's grain loss. Loss due to mechanical damage to the grains in manual threshing was observed to be very minimal and tolerable for all the varieties involved in this study. Therefore, in general, loss due to manual threshing comparable to and even larger than that of harvesting related losses. This implies that threshing can be considered as one of the critical losses point in the post-harvest practice of sorghum handling. Both variety and harvesting time have significant effect on threshing related loss due to scattering of grains and weak threshing efficiency of traditional practices. To overcome both limitations it is better to use mobile small or medium scale hand or motor driven multi-crop threshers. Apart from reduction of loss, using the threshers helps to save time and labour.

3.4 Loss during winnowing and cleaning

Analysis of variance for grain loss data for the traditional winnowing and cleaning method indicated a slightly significant ($P = 0.04$) effects as related to harvesting time and crop varieties (Table 3).

Table 3 Grain loss during traditional cleaning practices for different sorghum varieties harvested at different time intervals from total production

Sorghum variety (DM)	*Means of loss for different varieties at different harvesting time*		
	Early harvest (DM+2)	*Intermediate (DM+12)*	*Last harvest (DM+22)*
Makko (110)	3.49 ± 0.46^{AB}	3.36 ± 0.35^{A}	3.37 ± 0.52^{A}
Qaqqaba (119)	3.39 ± 0.17^{A}	4.05 ± 0.17^{C}	3.88 ± 0.23^{BC}
Malkam (117)	4.17 ± 0.58^{C}	3.23 ± 0.29^{A}	3.87 ± 0.43^{BC}

Notes: Values = Mean ± SD; DM = days to maturity; superscript letter(s) in the table show significance of the differences; means with common letter(s) in superscripts have no significant difference.

The grain loss of traditional winnowing (cleaning) practice indicated a maximum of 4.17±0.58 in *Malkam* (DM+2) with the entire grand mean of 3.65% from the total potential production. A grand mean loss of 4.16±0.26% was registered from the net grain that entered the winnowing and cleaning process after threshing. This much of loss is significant and can be considered as one of the critical loss points in post-production practices of sorghum. Grains loss might be associated with less prediction potential of farmers for wind direction, wind speed, and traditional tools used during winnowing. From crop's perspective density of grains associated with variety, and stage of maturity linked with harvesting time could contributes for the significant variation of the loss.

It is difficult to avoid grain maturity variation during harvesting, as ripening of sorghum grain is not uniform among different heads, and within ears of a head (Adhir, 2003; John, 2021). The aerodynamic and physical properties of the grains can also be affected by ripening level at harvesting time and drying conditions of grain sorghum, which can further interact with varieties and affect cleaning properties. These combined with the apparent wind velocity at winnowing time can highly affect grain loss during cleaning. This result obtained little bit greater than the reported sorghum cleaning grain loss of 5% (Hodges et al., 2014) and above the cereal cleaning grain loss range of 2-5% indicated as summary of traditional practice-related cases reported (Mohammed, and Tadesse, 2018).

As indicated in Table 3 winnowing and cleaning can be considered as one of the critical loss points. To save grain at this stage of practice, it is recommended to use multipurpose mechanical thresher. The thresher will help to combine threshing, winnowing and cleaning in a single step operation to overcome the limitations of conventional practice for better yield and efficiency.

3.5 Pre-storage grain handling loss

Pre-storage grain handling loss (loss during bagging, loading and unloading, and transporting to home level storage place) was registered with very low mean values of non-significant differences, as observed in this study. The mean values of the total loss recorded at this stage was below 1% from both the net grain and the potential yield, with 0.69±0.079 and 0.58± 0.067% grand means, respectively. A mean loss below 1% of this stage was also reported for cereals in Ethiopia (FAO, 2013; Tadesse et al., 2017).

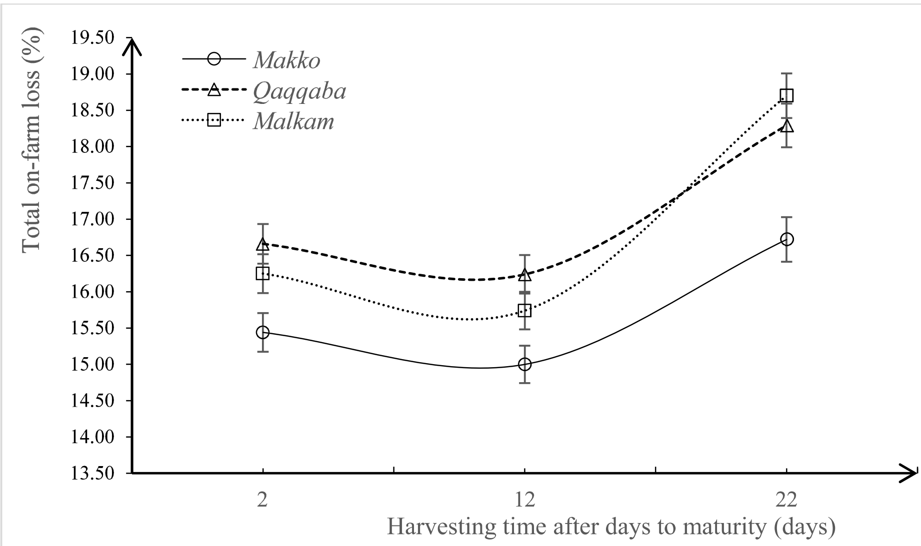
3.6 Grain loss from standing plots during days between levels of harvesting times

Significant preharvest grain loss was obtained during days of intervals between levels of harvesting time as estimates of grains per plot before harvest of the later harvesting levels indicated reduction from the initial estimated potential yield. The reduction in grain from the potential yield indicated significant mean differences with a grand mean of 2.23±1.63% due to a delay in harvesting time after maturity. The means of grain loss due to the delay of harvesting ranged from the minimum of 0.12± 0.02% registered on the second day after sampling for potential yield, i.e., at first harvesting time, to the maximum mean of 3.93 ±0.0.5% at the late harvesting time, which was 20 days after the first harvesting. This loss was mainly caused by birds and other insects consuming the grain while it was waiting for the determined intervals of harvesting time. Different researchers have described that extending time of harvesting after maturity heightens the risk of grain loss due to attack by birds and rodents though it may ensure good preservation due to drying (Mutungi et al., 2020).

3.7 Total on-farm postproduction loss

The total grain losses recorded during on-farm postproduction activities by traditional methods of the farmers' practices showed significant differences (P<0.01) that slightly decreased until the second harvesting intervals and then highly increased for the last harvesting (Figure 2).

Figure 2 Means of total on-farm grain loss of the varieties during post-production operations practiced by farmers as related to delay of harvesting time after DM



The estimate means of total on-farm grain loss decreased, significantly from an average 16.12% for early harvested produce to 15.66% at intermediate harvest and then increased to 17.90% for the last harvested produce. The total means were highest for *Qaqqaba,* medium for *Malkam* and lowest for *Makko* as related to varieties.

The total mean grain loss of *Malkam* variety was lower than that of *Qaqqaba* until the second harvesting time, but it increased after the second harvesting time and exceeded *Qaqqaba* for the third harvesting interval. The study reported for different cereal crops from Mali (FAO, 2020) indicated that variety and time of harvesting have significant impact on the levels of losses for all the on-farm operations. This result agrees with the lower range total on-farm sorghum grain loss (pre-storage loss) of 16.76, 18.34, 20.87 and 20.91% reported of survey study for Fadis, Alamata, Armachew, and Darashe districts, respectively in Ethiopia (FAO, 2017b). The recorded total on-farm grain loss is also in agreement with average pre-storage practices of postproduction loss of 15.73% sorghum grain and sesame seeds of 16.9% reported in Ethiopia (Tadesse et al., 2017; Kumera et al., 2020).

The overall average on-farm post-production loss of sorghum under traditional practices of the farmer has been summarised and presented in Table 4. The average percent share of each on-field operation stage from the total on-farm grain loss indicates the critical loss points to determine the priority area for intervention. This study results identified harvesting, threshing and winnowing with cleaning as the critical loss points which need immediate attention and intervention by introduction of improved methods. Vishwakarma et al. (2020), also indicated that harvesting and threshing as the two main critical loss points of postharvest value chain of sorghum.

Table 4 Summary of the average on-farm sorghum grain loss at each operation stage from grain at the stage and from the total potential yield

Post-production on-farm operation stages	*Loss from grain entered the stage (%)*	*Grain entered the stage (%)*	*Loss from the total yield (%)*
Loss during harvesting	4.60	100.00	4.60
Loss during field storage	1.90	95.40	1.82
Loss during threshing	6.31	93.59	5.91
Loss during cleaning	4.16	87.68	3.65
Pre-storage handling loss	0.69	84.03	0.58
Total loss of the yield			16.56

3.8 *Economics of the on-farm post-production grain loss*

The total quantity of on-farm post-production sorghum grain loss per hectare for individual farmer economic loss in the study area was calculated from the average yield of (ton/ha) obtained during this study, as indicated in Table 5.

Table 5 Economics of on-farm sorghum grain loss of the private farm during traditional post-production operation practiced by farmers in the study area

No.	*Stages of on-field grain loss investigated*	*Average loss (%)*	*Calculated loss (ton/ha)*	*Loss Value ($USD/ha)*
1	Harvesting related loss	4.60	0.210	136.50
2	Field storage loss	1.82	0.083	53.95
3	Loss during threshing	5.91	0.270	175.50
4	Loss during winnowing and cleaning	3.65	0.167	108.55
5	Pre-storage grain handling loss	0.58	0.027	17.55
6	Total on-farm post-production loss	16.56	0.757	492.05

The economics of on-farm post-production grain sorghum loss at the country scale was based on the annual sorghum production of the country. The total annual sorghum yields reported by the central statistical agency of the federal democratic republic of Ethiopia for four consecutive years from 2017/18 to 2020/21 growing years were 5.16, 5.02, 5.27 and 4.82 million tons, respectively (CSA, 2018, 2020, 2021). The annual national level on-farm postproduction sorghum grain loss (Table 6) was calculated from the above CSA data using the averages loss percents recorded (Table 4) for each of the on-field operation practiced by the farmers.

The national annual average price of 33,500 Birr/ton was computed from the information collected and used for price of grain loss indicated in this study. The price estimated in local currency (33,500 Birr/ton) was described in its equivalent USD Dollar ($650.00/ton) according to the exchange rate indicated by National Bank of Ethiopia ($1= 51.5385 ETB) on 25 May 2022, when the price data of this study was analysed.

Table 6 The total on-farm loss of sorghum grain in Ethiopia after production as calculated from the annual yield reported in the past four years (2018 to 2021)

Stages of postproduction on-farm operations	*Average loss (%)*	*On-farm postproduction grain losses (000 ton/year) as calculated from annual yield report*				
		2017/18	*2018/19*	*2019/20*	*2020/21*	*Average*
Annual yield reported		5,169.25	5,024.37	5,265.58	4,823.40	5,070.65
Loss related harvesting	4.60	237.79	231.12	242.22	221.88	233.25
Field storage grain loss	1.82	94.08	91.44	95.83	87.79	92.29
Loss during threshing	5.91	305.50	296.94	311.20	285.06	299.68
Winnowing/cleaning loss	3.65	188.68	183.39	192.19	176.05	185.08
Handling and transport loss	0.58	29.98	29.14	30.54	27.98	29.41
Total on-farm loss	16.56	856.03	832.04	871.98	798.76	839.70

Table 7 Annual national economic loss due to on-farm sorghum grain loss in Ethiopia during the traditional post-production methods practiced by farmers

No.	*Stages of on-field post-production investigated*	*Economic estimate of the country's annual post-production on-farm sorghum grain loss ($USD* x 10^6)*					
		2018	*2019*	*2020*	*2021*	*Sum*	*Average*
1	Harvesting loss	154.56	150.23	157.44	144.22	606.45	151.61
2	Field storage loss	61.15	59.44	62.29	57.06	239.94	59.99
3	Loss during threshing	198.58	193.01	202.28	185.29	779.16	194.79
4	Winnowing/cleaning loss	122.64	119.20	124.93	114.44	481.20	120.30
5	Handling and transport loss	19.49	18.94	19.85	18.18	76.47	19.12
6	Total on-farm loss	556.42	540.82	566.79	519.19	2183.22	545.80

Note: *During the analysis of this study, $1= 51.5385 ETB (according Ethiopian National Bank on 25 May 2022)

Using this best average price, the economic loss of the farmer due to on-farm post-production loss of sorghum grain indicated $492.05 USD per hectare. Maximum economic loss was incurred during threshing, followed by loss incurred during harvesting and cleaning, sharing 35.69%, 27.68% and 22.04% of the total indicated economic loss, respectively, corresponding to their listed order. Economic loss during threshing and cleaning together contributed 57.73% of the indicated total loss per hectare production at the study location. The result of economic loss estimated at the country level due to the on-farm post-production loss of sorghum grain indicated an average of $545.80 million USD loss per year for the country, while the four-year cumulative loss (2017/18 to 2020/21) was $2.183 billion USD (Table 7).

Generally, important information has been generated concerning on-farm sorghum grain loss in Hararge lowlands. The annual on-farm sorghum grain loss and its economic impact at the country level is also estimated based on the recorded experimental data. However, extrapolation of the national level on-farm post-production loss from data of specific location using production of few sorghum varieties might be major limitations of this study.

4 Conclusions

The studied post-production on-farm grain loss of the traditional farmers' practices conducted on three early maturing sorghum varieties indicated high total grain loss of 16.56% with the highest average of 17.06% at variety level recorded for *Qaqqaba*. Threshing stage is the most critical point with average grain loss of 5.91% followed by harvesting (4.60%). Other postharvest stages also contributed their part for the total loss. From results of this study attempts were made to extrapolate the economic impact of on-farm post-production losses. When this rate extrapolated to the country level based of CSA data, the country could experience estimated quantitative loss of 839,700 MT with estimated economic loss of 30.03 billion ETB (0.546 billion USD). However, this magnitude of loss can be minimised through conducting harvesting of sorghum head between DM+7 to DM+13 and through use of small scale multi-crop thresher.

Harvesting time of 7 to 13 days after DM are recommended for the studied sorghum varieties to minimise post-production on-farm grain loss under practices of the farmers. However, the grain losses recorded due to traditional threshing and cleaning practices are tremendous and introduction of improved methods like small scale sorghum threshers are highly recommended to reduce the losses.

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