Journal of Stored Products Research 114 (2025) 102794

Contents lists available at ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

Evaluation of corn drying and storage techniques to mitigate damage and total aflatoxin contamination in Mozambique

Cláudio Matusse[a,b,c], João Bila[d,e], Custódia Macuamule[f], Ana Sampaio[c,g,h], Armando Venâncio[i,j], Paula Rodrigues[a,*]

[a] CIMO, LA SusTEC, Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253, Bragança, Portugal
[b] Department of Agriculture, College of Business and Entrepreneurship of Chibuto, UEM-Eduardo Mondlane University, Gaza, 1200, Mozambique
[c] University of Trás-os-Montes and Alto Douro (UTAD), Quinta de Prados, 5000-801, Vila Real, Portugal
[d] Department of Crop Protection, Faculty of Agronomy and Forestry Engineering, UEM-Eduardo Mondlane University, Maputo, 1102, Mozambique
[e] Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN), UEM-Eduardo Mondlane University, Maputo, 1102, Mozambique
[f] Department of Animal Production and Food Technology, Faculty of Veterinary, UEM-Eduardo Mondlane University, Maputo, 1102, Mozambique
[g] Centre for the Research and Technology of Agro-Environmental and Biological Sciences (CITAB), UTAD, Quinta de Prados, 5000-801, Vila Real, Portugal
[h] Laboratório Associado Instituto Para a Inovação, Capacitação e Sustentabilidade da Produção Agroalimentar (Inov4Agro), UTAD, Quinta de Prados, 5000-801, Vila Real, Portugal
[i] CEB—Centre of Biological Engineering, University of Minho, 4710-057, Braga, Portugal
[j] LABBELS—Associate Laboratory, 4800-058, Guimarães, Portugal

ARTICLE INFO

Handling Editor: Dr Manoj Nayak

Keywords:
Corn
Grain drying
Safe storage
Post-harvest
AgraStrip

ABSTRACT

Contamination of corn by molds and aflatoxins is a major problem in Mozambique, and appropriate drying and storage of this essential food crop is crucial. This study aimed to evaluate the effects of different drying and storage techniques traditionally employed by smallholder farmers in the province of Gaza, Mozambique, in preventing degradation and aflatoxin contamination of corn. Two trials, one for drying and one for storage, were carried out in 2024 and 2025, based on the information resulting from interviews applied to 90 farmers. For corncob drying, three methods were tested: ground, straw mat and tarpaulin. For grain storage, hermetic (metallic drums and PICS bags) and non-hermetic (raffia bags and traditional barns) methods were tested for 12 months of storage. Grain moisture, damage and total aflatoxins were evaluated. All drying methods resulted in a sharp corn moisture reduction, but tarpaulin drying showed the lowest grain damage. No significant differences were observed in aflatoxin content between drying methods. For storage, corn grains (initial 12 % moisture content) stored in metallic drums and hermetic bags were intact after 12 months, while storage in traditional barns and raffia bags resulted in highly (60–80 %) and completely (100 %) damaged grain after 3 and 6 months, respectively. Corn stored in raffia bags showed the highest aflatoxin contamination levels. This study confirmed tarpaulin and hermetic technologies as the most effective methods of corn drying and storage. However, information, demonstration and training are still required for farmers to implement these technologies, which are more expensive than the less effective ones.

1. Introduction

Corn (*Zea mays* L.) has a fundamental and growing role in global agri-food systems, making it an increasingly important global staple, mostly in the Sub-Saharan Africa (SSA) (Erenstein et al., 2022). However, due to the hot and humid climate of the SSA, corn becomes highly susceptible to fungal contamination, which is an important driver of food loss in the region (Kortei et al., 2023). Also, fungi are not only responsible for corn deterioration with visible and measurable loss, but they also produce toxic metabolites, mycotoxins. Mycotoxins are secondary metabolites produced during the fungal infection of food products that are toxic to living beings, and chronic exposure to food contaminated with mycotoxins can result in the bioaccumulation of these toxins, posing substantial risks to public health (Li et al., 2025). Aflatoxins are of

* Corresponding author.
E-mail addresses: matusseclaudio8@gmail.com (C. Matusse), jbilay@gmail.com (J. Bila), custodiamacuamule@gmail.com (C. Macuamule), asampaio@utad.pt (A. Sampaio), avenan@deb.uminho.pt (A. Venâncio), prodrigues@ipb.pt (P. Rodrigues).

https://doi.org/10.1016/j.jspr.2025.102794
Received 29 May 2025; Received in revised form 20 August 2025; Accepted 22 August 2025
Available online 25 August 2025
0022-474X/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

particular care, given the significant toxicological effects and the high occurrence in many crops. The pathological effects include hepatoxicity, bile duct hyperplasia, kidney and intestinal tract hemorrhage and carcinogenesis (CAST, 2003). There are four main aflatoxins – aflatoxin B1 (AFB1), aflatoxin B2 (AFB2), aflatoxin G1 (AFG1) and aflatoxin G2 (AFG2) (Rodrigues et al., 2012), being AFB1 the most carcinogenic one (CAST, 2003). Most policy makers (e.g., the European Union and the Codex Alimentarius) regulate the limit for AFB1 and for the sum of the four aflatoxins (total aflatoxins, AFT) (FAO, 2004; EC, 2023). The Codex Alimentarius stipulated for African countries an AFT maximum tolerable limit of 15 μg/kg for corn (FAO, 2004).

Climate change is leading to increased accumulation of mycotoxins in crops. While some mycotoxins can contaminate maize before harvest, their levels can increase during the post-harvest stages as a result of the interrelationships between biotic and abiotic factors in storage, mostly in smallholder farmhouses, where appropriate drying and storage conditions are not always met (Chulze, 2010; Fleurat-Lessard, 2017). To reduce post-harvest losses in small farmers' warehouses, a greater understanding of socio-economic perspectives must be integrated into interventions aimed at protecting stored products (Makinya et al., 2021).

There are several types of drying and storage methods available for grains, employing different levels of technology. Rural farmers use traditional storage systems to ensure the preservation of products, but insect infestations and fungal infections remain a serious problem that threatens food security (Ng'ang'a et al., 2016). Post-harvest fungal and mycotoxin mitigation strategies include temperature, moisture and insect control during drying and storage. Drying is a key step in the preservation of corn grains and is required for long-term storage, as grain moisture is the main factor that makes the environment favorable for the development of insects and microorganisms (Ziegler et al., 2021). The grain's moisture content in storage must be below 14 % to avoid development of fungi and aflatoxins production (Magan and Aldred, 2007; Ng'ang'a et al., 2016). The recommended moisture content for stored corn grain is below 13.5 % (Walker et al., 2018), however, this is dependent on the environmental temperature, and the corn kernel becomes more susceptible to aflatoxin contamination when the temperature is warm (Richard, 2007). At 30 °C, only a 12 % or lower moisture content guaranties good preservation for up to 12 months (Fleurat-Lessard, 2017). Also, an adequate corn drying step before storage must ensure that the moisture content is less than 15 % within 10 days of drying and between 11 and 13 % within 20 days to avoid fungal and aflatoxin contamination (Atungulu et al., 2018).

Considering storage, one practical option that protects cereals from a variety of harmful environmental effects is the use of Purdue Improved Crop Storage (PICS®) hermetic bags or metallic drums (Lane and Woloshuk, 2017), but farmers are not always available to opt for more expensive, even if more effective, storage materials or conditions.

In Mozambique, corn is an essential agricultural and food product for most farmers and consumers (MADER, 2021). In 2022, the country had an average maize (corn) domestic supply of 2.2 million tons, representing a food supply of 56.2 kg/capita/yr and a significant energy supply of 489 kcal/capita/day (FAOStat, https://www.fao.org/faostat/en/#home, accessed April 21, 2025). The consumption of maize is of particular importance in rural households, which represent 61 % of the population. This is of major significance when 24.8 % of the Mozambican population (8.2 million people) is severely or moderately undernourished (Global Hunger Index, https://www.globalhungerindex.org/mozambique.html, accessed June 24, 2025). In Mozambique, agricultural production in general and maize (corn) in particular is affected by the global warming that is taking place in the country and this phenomenon is influenced by the relative proximity of all regions of Mozambique to the heat reservoir in the southwestern Indian Ocean, which keeps temperatures warm at the surface (Harrison et al., 2011).

A recent study revealed extremely high aflatoxin contamination of corn produced in two provinces of south Mozambique, Gaza and Inhambane, with medians ranging from 6.5 to 66.5 μg/kg, and samples showing values as high as 9200 μg/kg (Matusse et al., 2024). Levels higher than the maximum tolerable levels (MTLs) recommended by the Codex Alimentarius Commission for cereals and pulses and applied in the country (15 μg/kg; FAO, 2004) were observed in up to 90 % of the corn samples (Matusse et al., 2024). The level of AFT contamination in corn produced and consumed in these provinces constitutes a public health risk, specifically for the rural population, and risk mitigation strategies are urgently required.

Although, historically, all forms of long-term storage require adequate drying prior to storage, most developing countries face enormous quality control and food safety challenges (Villers, 2014). In Mozambique, small-hold and subsistence farmers are predominant, and there is a general poor compliance with good post-harvest management practices, resulting in high post-harvest losses. Lack of awareness of post-harvest losses and limited financial capacity to establish appropriate drying and storage technologies are among the main causes of post-harvest losses (CEAGRE, 2021a). The post-harvest attack on corn by aflatoxins in Mozambique is a reality that requires more attention and there is a need to find the best mitigation strategies that are sustainable for the reality of local producers, sellers and consumers (Matusse et al., 2024). This study aimed to determine the local and traditional drying and storage practices used by small hold farmers from the province of Gaza, south Mozambique, and to evaluate the efficacy of these practices in preventing degradation by fungi and insects and aflatoxin contamination of corn over 12 months of storage.

2. Materials and methods

2.1. Application of questionnaires to farmers

Prior to the installation of drying and storage trials, a questionnaire was applied to a group of selected farmers to obtain information and data on the drying and storage practices of the farmers from the province of Gaza. The application of questionnaires followed ethical standards, with all interviewees signing a consent form. It was carried out in the months of October and November 2022, in the province of Gaza, in the districts of Chokwé, Chonguene and Mandlakaze, following the methodology described by Bila et al. (2025). According to the Integrated Agrarian Survey (MADER, 2021), the province of Gaza has a total of 365, 593 farms, of which 95.43 % were small-sized farms, 4.5 % were medium-size farms and only 0.07 % were large farms. A confidence level of 90 % and an error of 10 % (0.1) were adopted to draw the sample. To calculate the sample size, the Yamane (1967) formula was used:

$$n = \frac{N}{1 + Ne^2}$$

where n is the sample size to be calculated; N is the relevant population; and e is the standard error (dependent on the desired degree of confidence).

Based on the formula, the sampling plan was established at a minimum of 75 surveys for small properties and 4 surveys for medium properties, totaling 79 surveys. Due to lack of representativeness, no large farms were selected for questionnaires. A total of 90 surveys were carried out per province, in case there were invalid surveys. The questionnaires were administered personally by the researcher in the local language (Chichangana), or in Portuguese in the case of producers who could speak the language (Bila et al., 2025).

2.2. Trial site and experimental conditions

Two consecutive trials were carried out. One on drying, with the aim of identifying the best way of drying the corn grain after harvesting, and the other on storage, which consisted of identifying the best method of storing the corn grain, according to some of the most common practices applied in the province of Gaza, Mozambique. The trials were conducted at the Chongoene farmhouse in October 2023 (drying trial) and from January 2024 to January 2025 (storage trial). Located in the south of the Gaza Province, the district of Chongoene is 15 km from the city of Xai-Xai. To the north, it is bordered by Chibuto District (Malehice Administrative Post), to the west by Xai-Xai District, to the east by Mandlakazi District and to the south by the Indian Ocean. The climate of the district of Chongoene is classified as Tropical Savannah (Köppen-Geiger climate classification Aw), with average temperature of 23.7 °C and annual rainfall of 714 mm (https://earthwise.bgs.ac.uk/index.php/Climate_of_Mozambique, accessed March 15, 2025). The region receives a rainfall pattern of high rainfall from December until April, with average temperatures ranging from 24 to 26 °C (max. 28 °C), and low rainfall from May until November, with temperatures ranging from 21 to 24 °C (max. 25 °C). The corn was harvested directly from the farmers' fields and transported to the trial site.

2.3. Experimental setup and sampling of drying trial

For the drying trial, three treatments were tested, with three repetitions each: drying corn cobs on a tarpaulin – T (Fig. 1A); drying corn cobs on the ground – G (Fig. 1B); and drying corn cobs on a straw mat – SM (Fig. 1C). The cobs were distributed evenly in the different areas of the test. The samples were set for continuous drying (both night and day), and the test site was monitored by a permanent person to prevent attack and theft. The wind pattern on the drying days blew from west to east, with the flow reaching an average speed of 14.6 km/h. During rainy periods, the grains were collected and reserved in a storehouse. Samples (cobs) were taken at the start of drying (day 0) and on days 3, 6, 10, 15 and 20. Four cobs were taken at each sampling time as shown in Fig. 2.

2.4. Experimental setup and sampling of storage trial

After determining the best drying technique, the storage trial followed, according to some of the most common practices used by small farmers in Mozambique. This trial was based on four treatments, each with three repetitions: storage in a raffia bag – RB; storage in hermetic bags – HB; storage in metallic drum – MD; and storage in traditional barns – TB. The raffia bags are made from polypropylene fibers, a type of tough, malleable plastic. Hermetic bags PICS® are trademarked hermetic bags made of two inner bags of high-density polypropylene with an outer woven polypropylene bag, and are non-toxic, odorless and colorless. Metallic drums are made of steel with a ribbed outer wall. Traditional barns are made from locally available materials (sticks, grass straw, extract from the epidermal part of shrub stems). All materials are available to corn producers in Mozambique. Fig. 3 illustrates the materials used and the experimental layout.

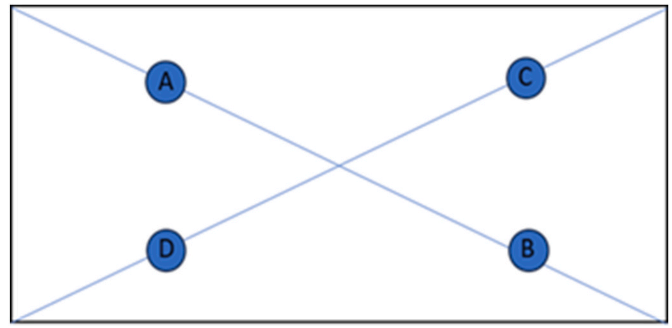

Fig. 2. Scheme of corn cobs sample collection. Four cobs at locations A, B, C and D of each drying system were collected at each sampling time.

Corn cobs were purchased from a local producer for the storage trial. The cobs were initially selected (Fig. 3A) and dried on tarpaulin (Figs. 3B), and 450 kg of grain were threshed from the cob (Fig. 3C). The threshed grain was further left to dry until it reached between 11 % and 12 % moisture content (Fig. 3D). Three hundred kg of cobs were left unthreshed and also dried to reach a similar moisture content. Three portions of grains (1 kg each) were taken as baseline (control) samples before loading the corn into the different storage systems. The quantities of corn deposited in each container were: 25 kg of grain in the raffia bag (Figs. 3E), 25 kg of grain in hermetic bag (Figs. 3F), 100 kg of grain in the metallic drum (Figs. 3G), and 100 kg of cobs in the traditional barn (Fig. 3H). The storage volume corresponds to the capacity of the containers that are available to local farmers. Three repetitions of each storage system were mounted (Fig. 3I and J). Raffia bags, hermetic bags and metallic drum were put inside the farmhouse storage room and the traditional barns were mounted on the outside. Samples (1 kg) of each storage condition were taken every three months for over one year [(4 treatments x 4 times) + 1 control] x 3 replicates, so a total of 51 samples were taken in the storage test.

2.5. Determination of grain moisture over time

In the drying trial, the cobs collected were threshed and the grain moisture content was determined in the field, immediately after sample collection, using a portable grain moisture analyzer (hygrometer; Wile65, Finland). The determination of moisture content followed the sequence of days established for sampling (on days 0, 3, 6, 10, 15 and 20). Moisture content was checked, and the principle of the procedure was to achieve 15 % moisture content in 10 days and between 11 % and 12 % in 20 days. In the storage test, the moisture content of corn samples was determined every three months for all conditions using the same equipment.

Fig. 1. Drying methods tested. **A:** tarpaulin (T); **B:** ground (G); **C:** straw mat (SM); **D:** trial layout.

Fig. 3. Corn and methods used for the storage trial. **A** and **B**: corn cobs being selected and dried before storage; **C** and **D**: dried and threshed corn prepared for storage; **E**: storage in raffia bag (RB); **F**: storage in hermetic bag (HB); **G**: storage in metallic drum (MD); **H**: storage in traditional barns (TB); **I** and **J**: trial layout.

2.6. Count of degraded grains and fungal contamination

For each sample, the incidence of fungal contamination in the grains was determined. To this end, the corn grains were homogenized before 100 grains were randomly selected. The incidence of fungi was quantified by visual inspection corresponding to the percentage of grains contaminated by fungi. The percentage of grains damaged by insects was also quantified.

2.7. Determination of total aflatoxin concentration

Total aflatoxin analyses in the drying trial were carried out immediately before drying (control T0 x 3 replicates) and when 15 % and 12 % moisture content was reached (10 and 20 days of drying, respectively) by corn grains of each drying method (3 methods x 3 replicates x 2 times = 18 samples), for a total of 21 samples. For the storage trial, total aflatoxins were analyzed for each sample, every three months throughout 1 year.

Before analysis, samples (1 kg) were homogenized and 100 g were ground to a fine flour using a Vevor grinder (model XZ-68, Shanghai, China). The sample extraction and aflatoxin analysis were made using the validated AgraStrip® Pro WATEX® (Romer Labs, Tulln, Austria) lateral flow procedure as described previously (Matusse et al., 2024). The procedure detects and quantifies total aflatoxins (AFT: AFB1 + AFB2 + AFG1 + AFG2), without discriminating each type of aflatoxin.

The limit of detection (LOD), the limit of quantification (LOQ), and the upper detection limit (UDL) for AFT were 1.0 μg/kg, 1.5 μg/kg and 50–100 μg/kg. Quantification was performed using the AgraVision™ Pro Reader (Romer Labs, Tulln, Austria). For results lower than the LOD, the value LOD/2 (0.5 μg/kg) was used, and for those between the LOD and the LOQ, the obtained value was used, as recommended by IPCS (2009).

2.8. Statistical analysis

The data from the drying and storage trials (grain moisture, damaged grains and aflatoxins) were tested for normal distribution with both the Kolmogorov-Smirnov and Shapiro-Wilk tests. When the data did not follow a normal distribution ($p < 0.05$), the data were log transformed (x+1) and the resulting data were tested for normality. If the log-transformed data failed the normality test, the non-parametric one-way ANOVA (Friedman test), followed by the Dunn's multiple comparison test for pair treatments comparisons, were used. When the data followed the normal distribution, one-way ANOVA or two-way ANOVA were used, followed by the Tukey's multiple comparisons test. All the analyses were done with the GraphPad Prism 10 for windows, version 10.4.2.

3. Results

3.1. Farmer's practices and knowledge on corn drying and storage

From the farmers interviewed, 37.8 % had producing areas smaller than 1 ha, and 55.6 % between 1 and 5 ha. Almost all farmers (98 %) produced corn and 93.3 % of these stored corn for family and animal consumption. Farmers referred that the produced corn is used for family food (all farmers) and animal feed (42.2 %), and sell part of their grain in the local informal (47.8 %) or formal (22.2 %) markets. The storage methods reported were traditional barn (35.4 %), metallic drum (24.4 % of the farmers), raffia bags (24.4 %), plastic bidons (8.5 %) and buckets (7.3 %). No farmers reported storage of their corn in hermetic bags. According to the farmers, the average storage duration of corn was 8.7 months, ranging from 2 to 36 months. Seventy-three percent of the farmers recognized that corn is frequently contaminated by fungi, and 41.6 % of these assume that they take the moldy part and consume the apparently healthy part. On the other hand, 42 % of the interviewed farmers estimate that production losses caused by fungi are below 25 %, while 37 % never accounted for losses. Considering farmers' knowledge about the factors that promote fungal contamination, 50 % respond that the main factor is the storage of wet crops or storage in wet environments (31.7 %) and the presence of rodents and birds (48.3 %) as well as insects (46.7 %) in the storage rooms.

Most farmers implement measures to reduce crop loss at different stages, before (68 % of the farmers), during (88 %) and after (88 %) harvest. To prevent fungal development, 87.3 % of the farmers dry the crops immediately after harvest, assess grains' moisture before storage (58.2 %), remove damaged grain before storage (58.2 %), protect from rain (53.2 %) and from rodents and birds (39.2 %), and store the grain in fresh and dry environment (30.4 %). Some farmers use insecticides (34.2 %) and fungicides (6.3 %) in their stored grain. Regarding general knowledge about fungi and mycotoxins, 68.9 % of the farmers showed insufficient knowledge about the conditions that promote fungal contamination, and 95.7 % don't know what strategies to adopt to avoid contamination, even though they empirically already use some. Eighty-eight percent had never heard of mycotoxins and none of the farmers had ever analyzed their grain for these compounds.

3.2. *Effect of drying system on grain moisture, decay and aflatoxin contamination*

Because corn grains were dried outdoors, the weather conditions were registered for the drying period (Fig. 4A). Under the tested drying conditions, the moisture content in corn grains at harvest was 19.4 %, and dropped to less than 15 % in only 3 days for all conditions (Fig. 4B). The tarpaulin samples were the ones that lost the highest percentage of weight (34 %), in opposition to the straw mat (31 %) and ground (28 %) samples. After 6 days, the grains moisture of tarpaulin-dried samples reached a moisture level below 13 % (12.7 % ± 0.1), contrary to the other two treatments that only reached less than 13 % after 10 days (straw mat, 12.7 % ± 0.1) or 15 days (ground, 12.4 % ± 0.3) (Fig. 4B). By day 10, samples from tarpaulin and straw mat had lost 36 % of their weight, while ground samples reached only 30 % of weight loss. By day 20, all conditions resulted in a final average moisture content between 11.8 % and 11.9 % (straw mat 11.86 % ± 0.6, ground 11.9 % ± 0.2, tarpaulin 11.8 % ± 0.7). It is worth noting that tarpaulin was the first method to achieve grain moisture below 12 % for all replicas (11.5 % ± 0.4), which occurred on day 15 (Fig. 4B). In the first three days of drying, the period when moisture loss in the grains was greatest, relative humidity (RH) was around 30 % and the maximum temperature 30 °C. On the sixth day, the RH increased to 70 % due to heavy rain, and the maximum temperature dropped (20 °C). After that, the RH was always above 50 %, which contributed to reducing the drying speed of grain.

The non-parametric one-way ANOVA (Friedman test) showed significant differences among the drying treatments ($F_R = 32.74$; $P < 0.0001$). The post hoc Dunn's multiple comparison test pointed out significant differences between tarpaulin vs. ground and tarpaulin vs. straw mat, but not between ground vs. straw mat (Table 1 and Fig. 4C).

Throughout drying, the apparent damage of the grains and the total aflatoxin concentration were measured in three sampling times: day 0 (control), where moisture content was 19.3 % ± 0.2 for tarpaulin, 19.0 % ± 0.9 for ground and 19.8 % ± 0.3 for straw mat, day 10 (10d; 12.4 % ± 0.2, 13.3 % ± 0.2 and 12.7 % ± 0.3, respectively) and day 20 (20d; 11.8 % ± 0.6, 11.9 % ± 0.2 and 11.8 % ± 0.7, respectively) (Fig. 5). The one-way ANOVA performed with the apparent damage (%)

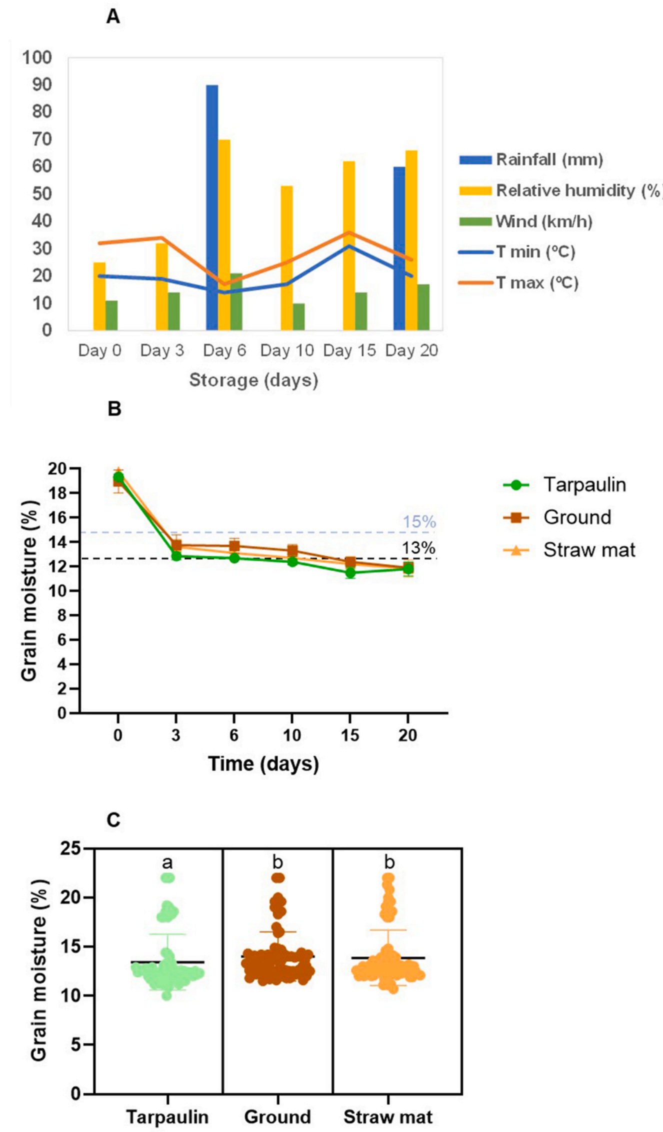

Fig. 4. **A**: Weather conditions during the drying period. **B:** Moisture content (%) of corn grains for the different drying techniques: tarpaulin, ground and straw mat (n = 3 per sampling time; average ± standard deviation) along 20 days; dashed lines indicate the moisture thresholds established for 10 days (15 %) and 20 days (12 %). **C:** Average (± standard deviation) grain moisture content by drying treatment (n = 72; 12 replicates per time, each replicate consisting of 4 corns cobs) taken along 20 days (0, 3, 5, 10, 15 and 20). The data were log (x+1) transformed; different letters indicate significant differences, by the Dunn's comparisons test, between the drying treatments.

Table 1
The Z- and p-values obtained in Dunn's post-hoc multiple comparison test, after nonparametric ANOVA analysis for drying treatments.

Treatments comparison	Z-value	p-value
tarpaulin vs. ground	5.375	<0.0001
tarpaulin vs. straw mat	4.125	0.0001
ground vs. straw mat	1.250	>0.05

logarithmized data showed significant differences among the drying treatments (F = 37,87; $p < 0.0001$). At 10 days no apparent damages were observed for any of the drying methods. At day 20 of drying, the condition with the lowest damage was the tarpaulin (T20d), differing ($p < 0.05$) from the ground (G20d) and the straw mat (SM20d) treatments

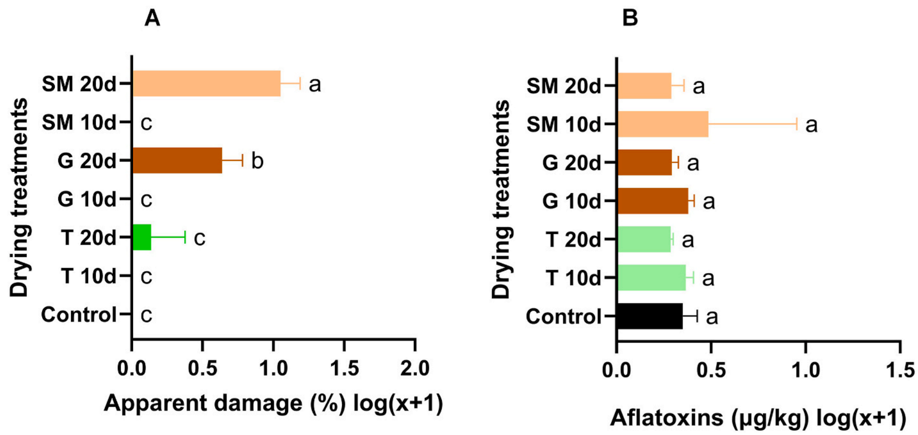

Fig. 5. Apparent damage (%) (**A**) and total aflatoxins (μg/kg) (**B**) at 0 (control), 10 days (10d) and 20 days (20d) of drying under different techniques. T – tarpaulin, G – ground, and SM – straw mat (n = 3; average ± standard deviation). The data were log (x+1) transformed before the one-way ANOVA analysis. Different letters indicate significant differences between the treatments by the Tukey's multiple comparison test.

(Fig. 5A). Despite the level of damage, the concentration of aflatoxins at days 10 and 20 showed no significant differences ($p > 0.05$) when compared to the concentration at day 0 (control, harvest time) (Fig. 5B), for all the three treatments. Nonetheless, even if not significant, higher concentrations of aflatoxins were registered in SM10d.

Although the ground samples showed higher grain moisture than the straw mat throughout the 20 days of trial, the latter recorded a significantly higher level of damage by the end of the trial. This should be the result of the high fungal development in the straw (Fig. 6), which increased the grain contamination. Straw mats are used to prevent corn cobs from coming into direct contact with the soil and its moisture. However, the straw mat absorbs moisture from the soil, promoting the development of fungi on its surface. These, in turn, will serve as inoculum for the contamination of the corn cobs. This situation may still result in increased contamination with mycotoxins, which was not observed in this study.

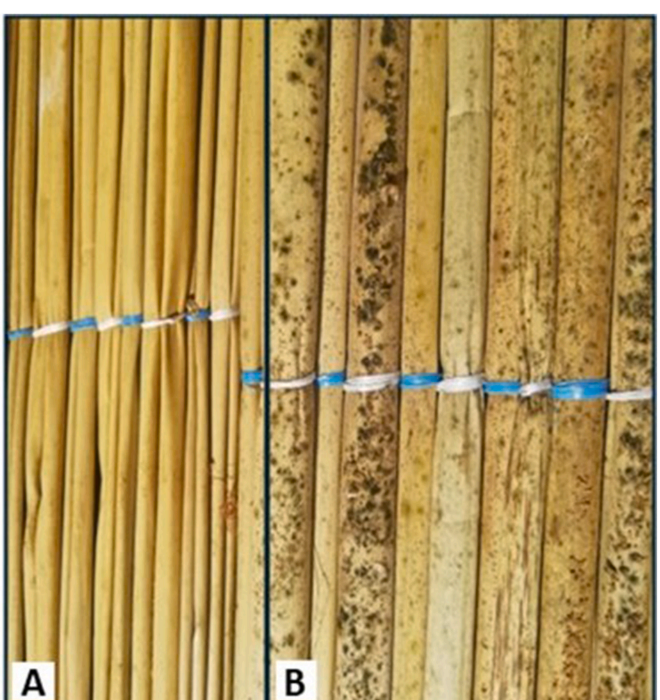

Fig. 6. Down-side of the straw mat at the beginning (A) and at the end (B) of the drying trial.

3.3. Effect of time and storage materials on grain damage and aflatoxin contamination

The initial (day 0) grain moisture used for the storage trial was 11.4 %, value that stabilized at 11 % in all treatments from the second time point of sampling (3 months) until the end of the trial (12 months). The mean percentage of damaged corn grains at the start of the trial was 0 % (Fig. 7A). After 3 months, damaged grains represented 54 % and 76 % for storage using the TB and the RB, respectively (Figs. 7A and 8). After 6 months of storage, all the grains (100 %) stored under these conditions were damaged. At this stage, the length of damage was such that it was impossible to discern between fungal contamination and other types of damage. For that reason, the results are presented as general damage, without differentiating fungal quantification. By contrast, grains in MD and HB exhibited a healthy aspect – without weevil and mold signs, characteristics that were maintained after 12 months storage (Figs. 7A and 8). The two-way ANOVA performed to analyze the apparent damage by storage treatments, time of storage and the interaction of both, measured significant differences ($p < 0.0001$) with treatments, time, and their interactions (Table 2). The type of storage is the source of variation that contributes 59.58 % of the total variation (Table 2), which emphasizes its importance.

The average concentration of total aflatoxins of the corn before storage was 1.30 ± 0.17 μg/kg (Fig. 7B). By the end of the 12 months of storage, aflatoxins were below the LOQ for all samples of the MD, HB, and TB storage methods (average 0.50 μg/kg), while RB showed average aflatoxin levels of 2.77 ± 1.50 μg/kg. Raffia bags were the only method where the aflatoxin concentration increased throughout time (Fig. 7B), The dynamics of aflatoxin concentration was variable over time. The two-way ANOVA performed to analyze the total aflatoxins by storage treatments, time of storage and the interaction of both, measured significant differences with treatments ($F = 7.860$; $p = 0.0090$), time ($F = 3.78$; $p = 0.0464$), and their interactions ($F = 3.96$; $p = 0.009$) (Table 2). The storage method contributes 41.99 % of the total variation, a trend also important in the apparent damage of corn grains (55.34 %). The one-way ANOVA, and the post-hoc Tukey analyses, showed significant differences among treatments, namely between RB and the remaining storage conditions.

4. Discussion

In the province of Gaza, southern Mozambique, most crop producers are smallholder farmers that follow a subsistence agriculture, and maize (corn) is produced by most of them as the major family and animal food. Although most farmers state to be aware of corn losses due to

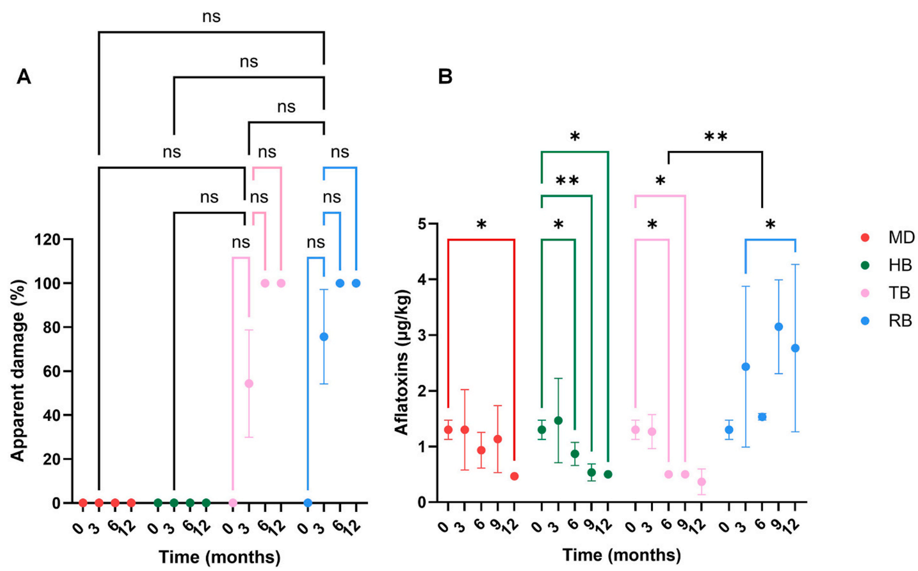

Fig. 7. **A:** Damaged corn grain percentages (%), and **B**. Aflatoxins concentration (µg/kg), throughout 12 months of storage and under different storage techniques. RB – Raffia bag, HB –Hermetic bags, MD –Metallic drum, and TB –Traditional barns. Data are expressed by the average (n = 3 based on three repetitions per sampling time ± standard deviation. Two-way ANOVA was computed, followed by Tukey's multiple comparisons per treatments and per time within each treatment. For simplicity, in A. only the non-significant (ns) Tukey pair comparisons are displayed, while in B. only the significant comparisons are displayed (asterisks indicate significant differences: *$p < 0.05$; **$p < 0.01$).

colonization by fungi, they do not perceive the true problem of mycotoxin occurrence. Many farmers segregate visibly damaged grains, but they do not recognize that just extremely infected grains are visually detected. As reported by Bila et al. (2025), the vast majority of farmers from the province of Gaza are unaware of the consequences of eating moldy food. These authors refer that only a minority of farmers (2.2 %) is aware of human or animal diseases caused by consuming contaminated food, and a significant proportion use contaminated products as human food (34.4 %) and animal feed (25.5 %). Besides lack of knowledge, Jolly et al. (2009) also reported that many African farmers acknowledge the consequences of ingesting contaminated food and appropriate practices for contamination control, but these practices are not always strictly respected.

Nearly half of the farmers interviewed are aware that the main factors that promote fungal infection of corn are inappropriate storage conditions, like storing wet grain and the presence of rodents, birds and insects, and most report that they do appropriate corn preparation before storage. Nonetheless, the traditional storage methods (raffia bags, traditional barns and metallic drums) are still employed for long-term corn storage, and none of the farmers use hermetic bags. CEAGRE (2021b) also stated that raffia/jute bags and traditional barns are the storing devices used by most small hold farmers, and that they are not ideal for preserving grain for a period longer than 3 months, since they don't prevent attacks from fungi, insects or rodents, and they don't control the effect of inadequate climatic factors such as high temperatures and high RH. Considering the period of corn storage reported by the farmers of up to 36 months (average 8.7 months), these storage conditions are inadequate and need to be adjusted to the needs.

Adequate drying and storage practices are required for corn availability throughout the year, until the following harvest, but traditional practices do not always allow for long and safe storage. Drying the grain before storage is necessary for appropriate preservation, especially in warm and humid countries like Mozambique. The initial moisture content of corn is usually around 20 % or higher, which renders the grain highly susceptible to fungal and insect infestation. Drying is thus required to reduce the moisture content to a safe level of at least 14 %. In the present study, 90 small and medium-size farmers of the province were interviewed to get detailed information about the storage practices traditionally used in the province and about the farmers' knowledge on fungi and mycotoxins contamination in corn. Most farmers reported drying the corn in the sun by distributing the cobs in thin layers on the ground, straw mats or tarpaulin, with the drying time depending on the weather conditions. Straw mats are produced by the farmers from local plant materials, in particular a highly available invasive species of sedge (*Cyperus rotundus* L.), and are generally used for grain drying purposes. Sun drying of corn cobs is inexpensive and generally used by small-scale farmers (de Groote et al., 2021), as other drying technologies like heat-dryers or fans are more expensive or not locally available for this type of farmers.

Our drying trial occurred in October, under dry and hot weather (maximum temperatures higher than 30 °C), using corn with initial moisture content of 19.4 %. These conditions have been reported as inducive for aflatoxin production by *Aspergillus flavus* (temperature above 25 °C and moisture content below 20 %; Palumbo et al., 2020). The aflatoxin levels at this timepoint were low (1.3 µg/kg), but detectable. The drying conditions allowed for rapid initial drying. Although there was heavy rainfall during the drying trial, the grain moisture content did not increase accordingly, since the cobs were collected into the warehouse during the rain. This is a common practice by the local farmers in rain situations, as they know that rain affects considerably the risk of fungal occurrence, even though they are not aware of aflatoxin occurrence.

To avoid fungal development and aflatoxin contamination, the moisture content during drying must be less than 15 % within 10 days (Atungulu et al., 2018). In this study, the moisture content after 10 days was below 13.3 % for all drying techniques (tarpaulin, ground, straw mats), producing an optimum initial moisture content that efficiently prevents fungal infection and reduces damage and losses during storage (Mukkun et al., 2018). In addition, in 20 days grain reached less than 12 %, which is considered optimal for storage for at least one year. Moisture of 14 % is considered safe for short-term storage of corn, but long-term storage requires moisture content of 13.5 % or below (Ng'ang'a et al., 2016). Nonetheless, differences were observed in the level of damage among drying conditions. Tarpaulin was effective in keeping a reduced level of damage, while the straw mat and the bare ground showed significantly higher grain damage.

Despite straw mats keeping the corn cobs away from dirt, the contact with the ground's humidity led to fungal development visually detected

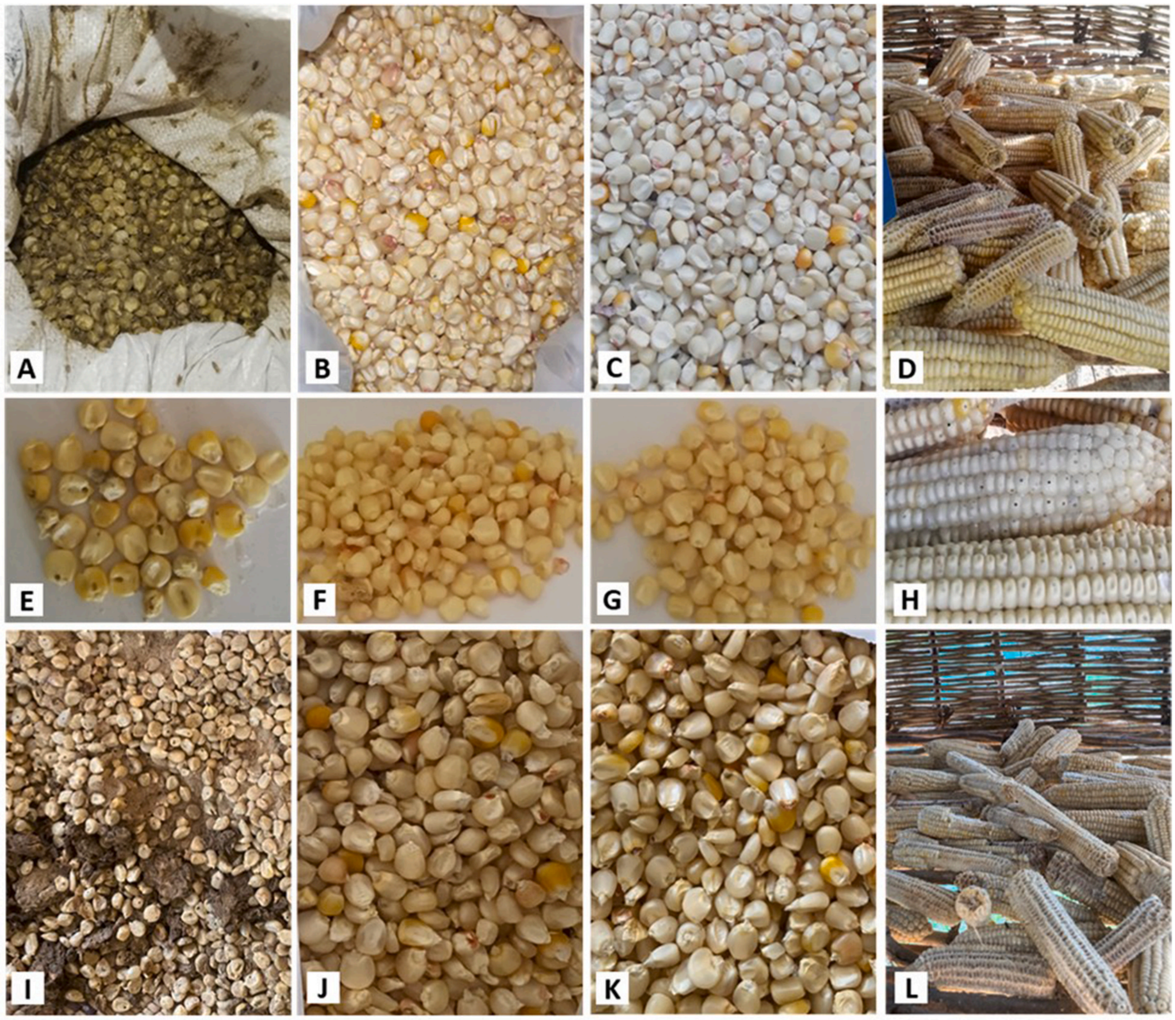

Fig. 8. Visual aspect of corn after 3 months (**A-H**) and 12 months (**I-L**) of storage under different methods. A, E and I: raffia bag (RB); B, F and J: hermetic bag (HB); C, G and K: metallic drum (MD); D, H and L: traditional barn (TB).

Table 2
Two-way ANOVA analyses for apparent damage and AFT in corn for 12 months. The source of variation, its percentage for the total variation (TV), F-values and p-values are also displayed.

Parameter	Source of variation	% TV	F-value	p-value
Apparent damage (%) log (x+1)	Time x Treatment	21.49	296.30	<0.0001
	Time	20.45	886.20	<0.0001
	Treatment	55.34	267.32	<0.0001
	Replica	0.5523	1	>0.05
AFT (μg/kg)	Time x Treatment	21.96	3.96	0.0009
	Time	6.999	3.78	0.0464
	Treatment	41.99	7.86	0.0090
	Replica	14.25	3.85	0.0029

in the mat, which potentially served as a means of transference to the cobs, increasing fungal contamination. In terms of aflatoxin contamination, despite the higher apparent damage observed in some conditions, very low contamination was reported, with no differences observed between treatments, probably resulting from the rapid moisture loss, which inhibited mycotoxin metabolism. Although more expensive than the straw mats (tarpaulins' price can vary from 600 to 1000 meticals – around 8 to 13 euros, exchange rate at June 26, 2025 - per 3 × 3m^2 unit), tarpaulin is locally available for farmers and has several technical advantages over straw mats or bare ground: is impermeable to ground humidity, promotes faster drying to adequate levels, facilitates rapid removal whenever necessary (e.g. rainy periods), protects grain from dirt, and is durable for many years of usage. Despite implying greater initial investment by farmers, tarpaulin will promote better health conditions of dried corn, which will promote lower corn losses during storage. Whenever possible, this material should be employed as the most appropriate drying surface.

After sun drying, the most significant storage methods used by the local farmers are, as determined by the interviews, RB, MD and TB. Field trials on storage methods traditionally used were thus established based on the results obtained in the interviews. Hermetic PICS bags, although not commonly used locally, were included in the trial. Also, typical storage periods were found to be 9 months on average, and some farmers stored the corn for up to 36 months. It is well established that longer storage periods are associated with higher risk of fungal growth and aflatoxin contamination (Kaaya and Kyamuhangire, 2006; Ng'ang'a et al., 2016; Kamel et al., 2024), and that this risk is correlated with the type of storage conditions, so storage practices that are easily available to farmers but are also appropriate for long storage are required.

Several studies, including two from Mozambique (Guenha et al., 2014; Njoroge et al., 2014; Williams et al., 2014; Nguenha et al., 2023), report that HB provide an adequate and affordable solution for post-harvest management of grain storage as they were demonstrated to provide excellent protection against insect infestation. In Mozambique, Guenha et al. (2014) found that rice storage in HB was more efficient than RB in protecting the grain, contributing to a reduction in insect infestation. Also in Mozambique, over a six-month storage period, the Super Grain Bag, polyethylene drum and polyethylene silo tank effectively limited the multiplication of insects and minimized damage in corn kernels (Nguenha et al., 2023).

Mold growth and aflatoxin production were also successfully tested across a wide range of grain moisture conditions when compared to non-hermetic containers (e.g. Walker et al., 2018; Kamel et al., 2024; Atnafu et al., 2025), but no studies are known from Mozambique in this specific approach. Our results demonstrate the ability of both types of hermetic containers (HB and MD) to prevent moisture migration during storage, as moisture was kept stable at 11 % for the 12 months of storage. Tubbs et al. (2016) and Walker et al. (2018) reported that, even when opening the bags weekly or monthly, moisture content of the grain was not affected, suggesting that routine opening will not result in a significant increase in grain moisture, especially if the grain is dried to at least 15 % moisture. Considering insects, Chigoverah and Mvumi (2016) tested high-pressure (artificial) insect infestation in hermetic (Super Grain Bags, SGB™) and non-hermetic bags, and observed a high number of insect perforations, high insect populations and moldy grain at trial termination, even in the hermetic bags. In our study, a very strong insect infestation was observed for RB and TB (non-hermetic) even after just 3 months of storage. On the contrary, HB and MD were able to keep the appropriate conditions to avoid fungal and insect infestation. Non-hermetic containers allow gas exchanges with the outside, promoting higher oxygen levels in the internal container headspace and allowing for interior infestation to maintain their biological and feeding activity (Murdock et al., 2012; Murdock and Baoua, 2014). Bag perforation caused by inner insects and probably outer insect invasion observed in the RB (but not in HB) also promotes re-oxygenation of the inner atmosphere, resulting in increased insect and fungal population growth. This perforation effect and subsequent increased insect population was also observed by Rizwan et al. (2022) in non-hermetic propylene bags but not in PICS bags, as thin packaging materials are more prone to insect invasions (Li et al., 2014).

With regard to mold and aflatoxin contamination, triple-layer hermetic bags are able to maintain the quality of the corn, but only if the moisture content in storage does not exceed 13 % (Ng'ang'a et al., 2016). It has been reported that the effects of external humidity fluctuations and the spread of fungi to uninfected grains in the storage process can be effectively blocked by using PICS hermetic bags (Lane and Woloshuk, 2017). In addition, hermetic bags can be an alternative to chemical products, for efficient and safe storage (Yewle et al., 2022).

The results of this study showed that corn storage techniques using MD and HB are appropriate for maintaining corn quality regarding mold and aflatoxin contamination, as long as the grain moisture content is ideal (below 13 %). The same was observed by Walker et al. (2018), which demonstrated that PICS bags and metal silos had a similar effect in reducing insect infestation, hindering mycotoxin increases and keeping grain quality high. Contrary to our results, Worku et al. (2022) noted that the 100 kg airtight metal silos, which were only half-filled, were not as effective as the hermetic bags in controlling AFT accumulation in stored corn, probably due to the excess oxygen available in the headspace of the silo that resulted in moisture migration and condensation phenomena. Kalsa et al. (2019) reported similar problems in insect control for wheat stored in half-filled silos, thus reinforcing the importance of oxygen deprivation and adequate moisture content in the capacity of obtaining good quality long-term storage. In this matter, hermetic bags are not only flexible, which allows for volume adjustment, but are made of high-density polyethylene with low permeability to atmospheric gases (Murdock and Baoua, 2014). The residual respiration by insects, fungi and the grain itself leads to oxygen deprivation and increased carbon dioxide level, resulting in fungal inactivation or death, hence hindering mycotoxin production (Murdock et al., 2012; Rizwan et al., 2022; Worku et al., 2022).

In our study, the corn storage techniques using TB and RB were found inappropriate for maintaining the quality of corn, because during the first 3 months of storage the grain began to deteriorate sharply. This deterioration resulted from the non-hermetic nature of these materials that, as discussed before, allows gaseous exchange with the outer side of the bag, adjusting the inner side to fluctuations in environmental relative humidity (Bakhtavar et al., 2019; Kamel et al., 2024) and do not limit the oxygen inside (Kamel et al., 2024). Both parameters increase the risk of fungal infection and/or mycotoxin contamination. In addition, the presence of oxygen favors the development of insects, increasing corn damage (Weinberg et al., 2008; Murdock et al., 2012; Murdock and Baoua, 2014; Viebrantz et al., 2016; Kamel et al., 2024). Regardless of the level of grain moisture typical (<15 %) and recommended (<14 %), hermetic storage significantly reduces the increase in aflatoxin compared to raffia bags (Walker et al., 2018). Higher contamination with aflatoxins (AFB1, AFG1, AFB2 and AFG2) was also recorded in corn stored in conventional bags as compared to HB (Khalid et al., 2024). Hermetic bags are effective storage devices for containing the initial levels of aflatoxins and preserving the nutrients in the initially dry corn for 12 months (Worku et al., 2022).

Contrary to what is reported for Tanzania (Magembe et al., 2016), Kenya (Walker et al., 2018) or Ghana (Kortei et al., 2021, 2023), farmers from the Gaza province have insufficient knowledge of fungal and mycotoxin contamination of corn, as well as of the consequent economic losses and health-related problems, and the drying and storage practices are mostly applied to reduce visible insect damage and grain damage. They also refer to a lack of training in post-harvest management of their crops. Although national-wide projects have been implemented to increase the use of improved storage technologies like hermetic bags, small farmers tend not to embrace them in their practice, due to elevated cost but also to lack of appropriate information, demonstration and training. In fact, previous projects implemented in Mozambique (SUSTENTA and PROCAVA) distributed HB that benefited 54,000 small farmers and households in the country on a trial basis (MADER, 2025), but following the project there was no continuance of bags use. Also, these bags are commercially available in local markets, but farmers tend to not use them due to elevated cost when compared with other common materials. HB with a capacity of 50 kg are sold locally at 223.18 meticals (3 euros) per unit, while the RB cost 20 meticals (0.27 euros) per unit. In fact, studies from different Sub-Sahara African countries (Burkina Faso, Ethiopia, Kenya, Niger, Nigeria) noted that the low use of hermetic (PICS) bags among farmers was mostly related to limited access to finance for initial acquisition, and that the farmers' perception of high price negatively affected the decision to adopt this technology (Ibro et al., 2014; Nouhoheflin et al., 2017; Baributsa and Njoroge, 2020; Alemu et al., 2021). Alemu et al. (2021) reported that this storage technology showed the highest monetary gain when compared with no storage or traditional (non-hermetic) storage technologies even after a storage period of 9.6 months, due to lower grain loss and to better adjustment to household and market's needs. Other than the monetary gain of using improved storage technology, the health and social costs of the invisible threat posed by mycotoxin contamination have not been accounted for, but needs also to be considered.

The present work reinforces the significance of substituting the traditional storage practices by effective hermetic technologies for long-term storage of corn, even if at higher initial cost. This will greatly improve food safety and food security of small hold farmers and their families, by reducing losses and mycotoxin contamination of corn. The farmers' acceptance of new or improved storage devices will only hold possible with adequate education on post-harvest loss factors, with emphasis on the non-visible mycotoxin contamination, demonstration of the benefits from adopting them (reduction of insect and mold infestation and mycotoxin accumulation) when compared to the disadvantageous higher initial cost, and training on the adequate use of the improved storage devices (Omotilewa et al., 2019; Alemu et al., 2021).

Due to the low technical knowledge and financial availability of the local small hold farmers, technical and financial support from the framers' associations and provincial governments would be initially essential to stimulate farmers' adherence. Alemu et al. (2021) stated that farmers' awareness about improved storage techniques through extension information as well as belonging to a farmers' cooperative increased the likelihood of using PICS bags. Omotilewa et al. (2019) found that only 50 % of interviewed farmers from Ugafarmers' heard of PICS bags, and from those 92 % didn't use them because they were not aware where to buy or the bags were too expensive. They further concluded that subsidized households are more likely to buy an additional bag at commercial prices relative to the households with no subsidy who are equally aware of the technology.

Storage systems like hermetic bags and metal drums are thus good options to reduce post-harvest losses, maintain product quality and improve food safety and security for farmers and their families in southern Africa, and Mozambique in particular (Okparavero et al., 2024). To improve and guarantee food security of these populations, where corn is the staple diet of most people, integrated approaches to combat the threat of food loss and aflatoxin contamination are necessary (Hell and Mutegi, 2011). These approaches include proper drying to ensure moisture content of no more than 13 % in 10 days and 11 % within 20 days. There is also a need to integrate storage using hermetic bags and metallic drums into this approach to ensure the quality of the corn preserved for long periods.

CRediT authorship contribution statement

Cláudio Matusse: Writing – original draft, Investigation, Formal analysis. **João Bila:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Custódia Macuamule:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Ana Sampaio:** Writing – review & editing, Supervision, Formal analysis. **Armando Venâncio:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Paula Rodrigues:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Acknowledgements

This work was supported by the Foundation for Science and Technology (FCT, Portugal) and the Aga Khan Development Network [project Ref. FCT AGA-KHAN/541590696/2019 "MYCOTOX-PALOP – Multi-actor partnership for the risk assessment of mycotoxins along the food chain in African Portuguese-speaking countries (PALOP)"]. The authors thank FCT for financial support through national funds FCT/MCTES (PIDDAC) to CIMO (UIDB/00690/2020 and UIDP/00690/2020), SusTEC (LA/P/0007/2020), CITAB (UID/AGR/04033/2020), CEB (UIDB/04469/2020), LABBELS (LA/P/0029/2020) and Inov4Agro (LA/P/0126/2020). Cláudio Matusse thanks FCT for the PhD grant PRT/BD/15483/2022.

Nomenclature

AFB1	aflatoxin B1
AFB2	aflatoxin B2
AFG1	aflatoxin G1
AFG2	aflatoxin G2
AFT	sum of AFB1, AFB2, AFG1 and AFG2
G	ground
HB	hermetic bags
LOD	limit of detection
LOQ	limit of quantification
MD	metallic drum
MTL	maximum tolerable levels
PICS	Purdue Improved Crop Storage
RB	raffia bag
relative humidity	(RH)
SM	straw mat
SSA	Sub-Saharan Africa
T	tarpaulin
TB	traditional barns
TV	total variation
UDL	upper detection limit

Data availability

Data will be made available on request.

References

Alemu, G.T., Nigussie, Z., Haregeweyn, N., Berhanie, Z., Wondimagegnehu, B.A., Ayalew, Z., Molla, D., Okoyo, E.N., Baributsa, D., 2021. Cost-benefit analysis of on-farm grain storage hermetic bags among small-scale maize growers in northwestern Ethiopia. Crop Prot. 143, 105478. https://doi.org/10.1016/j.cropro.2020.105478.

Atnafu, B., Chala, A., Lemessa, F., Bayissa, W., Mohammed, A., Gerbaba, C.A., 2025. Effectiveness of storage facilities in managing toxigenic fungi and mycotoxins associated with stored maize (*Zea mays* L.) in Ethiopia. J. Stored Prod. Res. 111, 102561. https://doi.org/10.1016/j.jspr.2025.102561.

Atungulu, G.G., Olatunde, G., Wilson, S., 2018. Engineering methods to reduce aflatoxin contamination of corn in on-farm bin drying and storage systems. Dry. Technol. 36 (8), 932–951. https://doi.org/10.1080/07373937.2017.1365726.

Bakhtavar, M.B., Afzal, I., Basra, S.M.A., 2019. Moisture adsorption isotherms and quality of seeds stored in conventional packaging materials and hermetic Super Bag. PLoS One 14, e0207569. https://doi.org/10.1371/journal.pone.0207569.

Baributsa, D., Njoroge, A.W., 2020. The use and profitability of hermetic technologies for grain storage among smallholder farmers in eastern Kenya. J. Stored Prod. Res. 87, 101618. https://doi.org/10.1016/j.jspr.2020.101618.

Bila, J., Macuamule, C., Bombe, A., Ribeiro, M.I., Venâncio, A., Afonso, S., Rodrigues, P., 2025. Assessment of farmer's knowledge and attitudes towards fungi and mycotoxin contamination in staple crops in Southern Mozambique. Front. Sustain. Food Syst. 9, 1622532. https://doi.org/10.3389/fsufs.2025.1622532. ID.

CAST (Council for Agriculture Science and Technology), 2003. Mycotoxins risks in plant, animal, and human systems. Task Force Report 139. CAST, Ames.

CEAGRE, 2021a. Estratégia de Gestão Pós-Colheita (2020-2029). Análise da Situação de gestão Pós-colheita. Ministério de Agricultura e Desenvolvimento Rural, p. 87. Mozambique.

CEAGRE, 2021b. Estratégia de Gestão Pós-Colheita e Plano de Implementação. Ministério de Agricultura e Desenvolvimento Rural. Mozambique, p. 80.

Chigoverah, A.A., Mvumi, B.M., 2016. Efficacy of metal silos and hermetic bags against stored-maize insect pests under simulated smallholder farmer conditions. J. Stored Prod. Res. 69, 179–189. https://doi.org/10.1016/j.jspr.2016.08.004.

Chulze, S.N., 2010. Strategies to reduce mycotoxin levels in maize during storage: a review. Food Addit. Contam. 27 (5), 651–657. https://doi.org/10.1080/19440040903573032.

De Groote, H., Githinji, P.G., Munya, B.J., Ricker-Gilbert, J.E., 2021. Economics of open-air sun drying in the maize value chain of Kenya. J. Agric. Food Res. 5, 100185. https://doi.org/10.1016/j.jafr.2021.100185.

EC (European Commission), 2023. Commission regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing regulation (EC) No 1881/2006, 2023 OJEU L119, 103–157. Available online: https://eur-lex.europa.eu/legal-content/pt/TXT/?uri=CELEX%3A32023R0915.

Erenstein, O., Jaleta, M., Sonder, K., Mottaleb, K., Prasanna, B.M., 2022. Global maize production, consumption and trade: trends and R&D implications. Food Secur. 14 (5), 1295–1319. https://doi.org/10.1007/s12571-022-01288-7.

FAO, 2004. Worldwide regulations for mycotoxins in food and feed in 2003. FAO Food and Nutrition Paper 81. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fleurat-Lessard, F., 2017. Integrated management of the risks of stored grain spoilage by seedborne fungi and contamination by storage mould mycotoxins – an update. J. Stored Prod. Res. 71, 22–40. https://doi.org/10.1016/j.jspr.2016.10.002.

Guenha, R., Salvador, B.V., Rickman, J., Goulao, L.F., Muocha, I.M., Carvalho, M.O., 2014. Hermetic storage with plastic sealing to reduce insect infestation and secure paddy seed quality: a powerful strategy for rice farmers in Mozambique. J. Stored Prod. Res. 59, 275–281. https://doi.org/10.1016/j.jspr.2014.06.007.

Harrison, L., Michaelsen, J., Funk, C., Husak, G., 2011. Effects of temperature changes on maize production in Mozambique. Clim. Res. 46 (3), 211–222. https://doi.org/10.3354/cr00979.

Hell, K., Mutegi, C., 2011. Aflatoxin control and prevention strategies in key crops of Sub-Saharan Africa. Afr. J. Microbiol. Res. 5 (5), 459–466. https://doi.org/10.5897/AJMR10.009.

Ibro, G., Sorgho, M.C., Idris, A.A., Moussa, B., Baributsa, D., Lowenberg-DeBoer, J., 2014. Adoption of cowpea hermetic storage by women in Nigeria, Niger and Burkina Faso. J. Stored Prod. Res. 58, 87–96. https://doi.org/10.1016/j.jspr.2014.02.007.

IPCS (International Programme on Chemical Safety), 2009. Principles and methods for the risk assessment of chemicals in food. In: Environmental Health Criteria 240, second ed. WHO Press, Berlin, Germany.

Jolly, C.M., Bayard, B., Awuah, R.T., Fialor, S.C., Williams, J.T., 2009. Examining the structure of awareness and perceptions of groundnut aflatoxin among Ghanaian health and agricultural professionals and its influence on their actions. J. Socio-Econ. 38, 280–287.

Kaaya, A.N., Kyamuhangire, W., 2006. The effect of storage time and agroecological zone on mould incidence and aflatoxin contamination of maize from traders in Uganda. Int. J. Food Microbiol. 110 (3), 217–223. https://doi.org/10.1016/j.ijfoodmicro.2006.04.004.

Kalsa, K.K., Subramanyam, B., Demissie, G., Mahroof, R., Worku, A., Gabbiye, N., 2019. Evaluation of postharvest preservation strategies for stored wheat seed in Ethiopia. J. Stored Prod. Res. 81, 53–61.

Kamel, R.M., Assaha, D.V.M., El-kholy, M., Elsawy, H.I.A., 2024. Influence of maize (*Zea mays* L.) moisture content stored in various compacted multi-layer hermetic bags on seed quality and mycotoxins contamination. J. Stored Prod. Res. 107, 102319. https://doi.org/10.1016/j.jspr.2024.102319.

Khalid, E., Afzal, I., Khan, S.H.U., Awan, S.I., 2024. Comparison of hermetic and conventional bags for maize seed preservation in Azad Kashmir, Pakistan. J. Stored Prod. Res. 105, 102215. https://doi.org/10.1016/j.jspr.2023.102215.

Kortei, N., Atsugah, P.Y., Letsyo, E., Boakye, A.A., Tettey, C.O., Essuman, E.K., 2021. Knowledge and attitude of consumers about natural food toxins: a case of tertiary students in the Volta region of Ghana. J. Food Quality Hazards Control 8, 234–268. https://doi.org/10.18502/jfqhc.8.3.7196.

Kortei, N.K., Badzi, S., Nanga, S., 2023. Survey of knowledge, and attitudes to storage practices preempting the occurrence of filamentous fungi and mycotoxins in some Ghanaian staple foods and processed products. Sci. Rep. 13, 8710. https://doi.org/10.1038/s41598-023-35275-5.

Lane, B., Woloshuk, C., 2017. Impact of storage environment on the efficacy of hermetic storage bags. J. Stored Prod. Res. 72, 83–89. https://doi.org/10.1016/j.jspr.2017.03.008.

Li, K., Cai, H., Luo, B., Duan, S., Yang, J., Zhang, N., He, Y., Wu, A., 2025. Recent progress of mycotoxin in various food products — human exposure and health risk assessment. Foods 14 (5), 865. https://doi.org/10.3390/foods14050865.

Li, S.H., Kwon, S.J., Lee, S.E., Kim, J.H., Lee, J.S., Na, J.H., Han, J., 2014. Effect of type and thickness of flexible packaging films on perforation by *Plodia interpunctella*. Korean J. Food Sci. Technol. 46, 739–742. https://doi.org/10.9721/KJFST.2014.46.6.739.

MADER, 2021. Inquérito Agrário Integrado 2020 | Marco Estatístico. Ministério da Agricultura e Desenvolvimento Rural. Desenvolvimento Rural 88. Moçambique.

MADER, 2025. Programa Nacional de Integração da Agricultura Familiar em Cadeias de Valor Produtivas. SUSTENTA 2025, Ministério da Agricultura e Desenvolvimento Rural. Desenvolvimento Rural 62. Moçambique.

Magan, N., Aldred, D., 2007. Post-harvest control strategies: minimizing mycotoxins in the food chain. Int. J. Food Microbiol. 119, 131–139. https://doi.org/10.1016/j.ijfoodmicro.2007.07.034.

Magembe, K., Mwatawala, M., Mamiro, D., Chingonikaya, E., 2016. Assessment of awareness of mycotoxins infections in stored maize (*Zea mays* L.) and groundnut (*Arachis hypogea* L.) in Kilosa district, Tanzania. Int. J. Flow Control 3, 1–8. https://doi.org/10.1186/s40550-016-0035-5.

Makinya, K.J., Wagacha, J.M., Odhiambo, J.A., Likhayo, P., Edoh-ognakossan, K., Tefera, T., Abass, A., Mutungi, C.M., 2021. The importance of store hygiene for reducing post-harvest losses in smallholder farmers' stores: evidence from a maize-based farming system in Kenya. J. Stored Prod. Res. 90, 101757. https://doi.org/10.1016/j.jspr.2020.101757.

Matusse, C., Lucamba, Z., Bila, J., Macuamule, C., Sampaio, A., Afonso, S., Venâncio, A., Rodrigues, P., 2024. Aflatoxin contamination of various staple foods from Angola and Mozambique. Toxins 16 (12), 516. https://doi.org/10.3390/toxins16120516.

Mukkun, L., Lalel, H.J.D., Tandirubak, Y., 2018. Initial moisture content of corncobs plays an important role in maintaining its quality during storage. Agritech 38 (2), 167. https://doi.org/10.22146/agritech.26663.

Murdock, L.L., Baoua, I.B., 2014. On Purdue Improved Cowpea Storage (PICS) technology: background, mode of action, future prospects. J. Stored Prod. Res. 58, 3–11. https://doi.org/10.1016/j.jspr.2014.02.006.

Murdock, L.L., Margam, V., Baoua, I.B., Balfe, S., Shade, R.E., 2012. Death by desiccation: effects of hermetic storage on cowpea bruchids. J. Stored Prod. Res. 49, 166–170. https://doi.org/10.1016/j.jspr.2012.01.002.

Nguenha, R.J., Tivana, L.D., Viola, P.C.M., Monjane, I.J.B., Chemane, S.S.I., Kanfwanfwa, N., Ernesto, D.B., Lungu, O.N., 2023. High-density polyethylene containers and super grain bag reduce storage insect pests infestation in maize and preserve grain quality. Afr. J. Agric. Res. 19 (6), 662–674. https://doi.org/10.5897/ajar2023.16380.

Ng'ang'a, J., Mutungi, C., Imathiu, S., Affognon, H., 2016. Effect of triple-layer hermetic bagging on mould infection and aflatoxin contamination of maize during multi-month on-farm storage in Kenya. J. Stored Prod. Res. 69, 119–128. https://doi.org/10.1016/j.jspr.2016.07.005.

Njoroge, A.W., Affognon, H.D., Mutungi, C.M., Manono, J., Lamuka, P.O., Murdock, L.L., 2014. Triple bag hermetic storage delivers a lethal punch to *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in stored maize. J. Stored Prod. Res. 58, 12–19. https://doi.org/10.1016/j.jspr.2014.02.005.

Nouhoheflin, T., Coulibaly, J.Y., D'Alessandro, S., Aitchedji, C.C., Damisa, M., Baributsa, D., Lowenberg-DeBoer, J., 2017. Management lessons learned in supply chain development: the experience of PICS bags in West and Central Africa. Int. Food Agribus. Manag. Rev. 20, 427–438.

Okparavero, N.F., Otitodun, G.O., Rukayat, Q., Jimoh, O.M., Ishola, T.D., Okunlade, A.F., Haruna, P.B., Isaac, A.Y., Akande, E.T., 2024. Effective storage structures for preservation of stored grains in Nigeria: a review. Ceylon J. Sci. 53 (1), 139–147. https://doi.org/10.4038/cjs.v53i1.8194.

Omotilewa, O.J., Ricker-Gilbert, J., Ainembabazi, J.H., 2019. Subsidies for agricultural technology adoption: evidence from a randomized experiment with improved grain storage bags in Uganda. Am. J. Agric. Econom. 101 (3), 753–772. https://doi.org/10.1093/ajae/aay108.

Palumbo, R., Gonçalves, A., Gkrillas, A., Logrieco, A., Dorne, J.-L., Dallasta, C., Venâncio, A., Battilani, P., 2020. Mycotoxins in maize: mitigation actions, with a chain management approach. Phytopathol. Mediterr. 59 (1), 5–28. https://doi.org/10.36253/phyto-11142.

Richard, J.L., 2007. Some major mycotoxins and their mycotoxicoses—An overview. Int. J. Food Microbiol. 119, 3–10. https://doi.org/10.1016/j.ijfoodmicro.2007.07.019.

Rizwan, M., Atta, B., Ali, M.Y., Ashraf, I., Arshad, M., Tahir, M., Rizwan, M., Sabir, A.M., Shehzadi, N., Khalid, U.B., Iqbal, S., Pan, M.-Z., Liu, T.-X., 2022. The comparison of interstitial relative humidity and temperatures of hermetic and polypropylene bag for wheat grain storage under different agro-climatic conditions of rice-wheat ecosystem of Pakistan: effect on seed quality and protection against insect pests. J. Stored Prod. Res. 96, 101936. https://doi.org/10.1016/j.jspr.2022.101936.

Rodrigues, P., Venâncio, A., Lima, N., 2012. Aflatoxigenic fungi and aflatoxins in portuguese almonds. Sci. World J. 9. https://doi.org/10.1100/2012/471926. Article ID 471926.

Tubbs, T., Baributsa, D., Woloshuk, C., 2016. Impact of opening hermetic storage bags on grain quality, fungal growth and aflatoxin accumulation. J. Stored Prod. Res. 69, 276–281. https://doi.org/10.1016/j.jspr.2016.10.003.

Viebrantz, P.C., Radunz, L.L., Dionello, R.G., 2016. Mortality of insects and quality of maize grains in hermetic and non-hermetic storage. Rev. Bras. Eng. Agrícola Ambient. 20 (5), 487–492. https://doi.org/10.1590/1807–1929/agriambi.v20n5p487-492.

Villers, P., 2014. Aflatoxins and safe storage. Front. Microbiol. 5, 1–6. https://doi.org/10.3389/fmicb.2014.00158.

Walker, S., Jaime, R., Kagot, V., Probst, C., 2018. Comparative effects of hermetic and traditional storage devices on maize grain : mycotoxin development , insect infestation and grain quality. J. Stored Prod. Res. 77, 34–44. https://doi.org/10.1016/j.jspr.2018.02.002.

Weinberg, Z.G., Yan, Y., Chen, Y., Finkelman, S., Ashbell, G., Navarro, S., 2008. The effect of moisture level on high-moisture maize (*Zea mays* L.) under hermetic storage conditions-in vitro studies. J. Stored Prod. Res. 44, 136–144. https://doi.org/10.1016/j.jspr.2007.08.006.

Williams, S.B., Baributsa, D., Woloshuk, C., 2014. Assessing Purdue Improved Crop Storage (PICS) bags to mitigate fungal growth and aflatoxin contamination. J. Stored Prod. Res. 59, 190–196. https://doi.org/10.1016/j.jspr.2014.08.003.

Worku, A.F., Kalsa, K.K., Abera, M., Tenagashaw, M.W., Habtu, N.G., 2022. Evaluation of various maize storage techniques on total aflatoxins prevalence and nutrient preservation. J. Stored Prod. Res. 95, 101913. https://doi.org/10.1016/j.jspr.2021.101913.

Yamane, T., 1967. Statistics, an Introductory Analysis, second ed. Harper and Row, , New York.

Yewle, N., Chandra Swain, K., Mann, S., Guru, P.N., 2022. Performance of hermetic bags in green gram [*Vigna radiata* (L.) R. Wilczek] storage for managing pulse beetle (*Callosobruchus chinensis*). J. Stored Prod. Res. 95, 101896. https://doi.org/10.1016/j.jspr.2021.101896.

Ziegler, V., Paraginski, R.T., Ferreira, C.D., 2021. Grain storage systems and effects of moisture, temperature and time on grain quality - a review. J. Stored Prod. Res. 91, 101770. https://doi.org/10.1016/j.jspr.2021.101770.