



Hermetic storage technologies preserve maize seed quality and minimize grain quality loss in smallholder farming systems in Mexico

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ABSTRACT

Reducing maize postharvest storage losses is a challenge for millions of smallholder farmers in Mexico. A previous study documented the effects of storage technologies on stored grain losses. The current study follows up on those experiments to evaluate the effectiveness of diverse storage technologies — polypropylene bags with and/or without insecticide, hermetic metal silos, hermetic bags, recycled plastic containers, silage plastic bags, micronized lime, and standard lime — in maintaining grain and seed quality during 2017 and 2018 at six sites: three agroecologies below 500 m above sea level (masl) and three agroecologies above 2000 masl. Maize samples stored using each of the above technologies were collected before and after six months of storage. Pest-free samples were analyzed for grain composition (starch, protein, oil, ether extracts, polyphenols contents), selected physicochemical parameters (fat acidity, an indicator of biochemical changes during storage; hundred kernel weight; flotation index, an indirect parameter of grain density; color; and germination. Storage technologies did significantly affect macronutrient content, but the quality of grain stored under non-hermetic conditions was reduced, as reflected in significantly increased fat acidity and flotation index. Seed germination was less affected by the type of storage technology at sites above 2000 masl but a significant effect was observed at sites below 500 masl. On average, the germination capacity of seed stored using non-hermetic technologies (polypropylene bags with or without insecticide or lime) dropped 56% at lowland sites, as compared to 2.8% for seed stored using hermetic metal silos or hermetic bags. Airtight technologies also minimized quality losses by reducing metabolic activities. By limiting insect and fungi infestation and reducing quantity and quality degradation in stored maize, hermetic technologies can contribute to Mexican smallholder farmers' food security.

CRedit authorship contribution statement

Sylvanus Odjo: conceptualization, methodology, investigation, data collection, data curation, formal analysis, visualization, writing - original draft, writing - review & editing. **Natalia Palacios Rojas:** methodology, investigation, supervision, writing - review & editing. **Juan Burgueño:** methodology, formal analysis, writing - review & editing. **Marina Corrado:** methodology, investigation, data collection, writing - review & editing. **Tim Ortner:** data collection, writing - review & editing. **Nele Verhulst:** conceptualization, methodology, investigation, project administration, supervision, writing - review & editing.

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1. Introduction

Postharvest grain or seed losses generally refer to reductions in quantity and quality throughout the postharvest system and can diminish farmers' food supplies and the safety and market value of grain, causing significant economic losses (Hodges et al., 2011). Food losses in weight or volume are easy to measure but altered grain or seed quality are complex, difficult to assess and depend on whether the grain is for human or animal consumption or for seed. For grain, qualities such as color, flavor, or nutritional value govern consumer acceptance and factors such as possible mycotoxin contamination can affect safety (Ekpa et al., 2019). For seed, germination percentage and seedling viability are the major concerns (Boxall, 2001).

Abbreviations

| | |
|--------|--|
| L* | Lightness color scale of the International Commission on Illumination (CIE) |
| a* | Redness color scale of the International Commission on Illumination (CIE) |
| b* | Yellowness color scale of the International Commission on Illumination (CIE) |
| ANOVA | Analysis of variance |
| CIE | International Commission on Illumination |
| CIMMYT | International Maize and Wheat Improvement Center |
| CV | Coefficient of variation |
| HBT | Hermetic bag with a tie-down system: GrainPro Hermetic SuperGrainbag® Farm |
| HBZ | Hermetic bag with a zip system: GrainPro hermetic SuperGrainbag® Premium RZ with zip |
| HMS | Hermetic metal silo |
| ISTA | International Seed Testing Association |
| masl | m above sea level |
| na | Not available |
| ns | No sufficient grain without apparent damage |
| PP | Polypropylene bag |
| PP_AP | Polypropylene bag with aluminum phosphide |
| PP_ML: | Polypropylene bag with micronized lime |
| PP_SL: | Polypropylene bag with standard lime |
| PBO | Plastic bottle |

Mexican smallholder maize farmers typically harvest one ton per hectare on average (Govaerts et al., 2019), much of it often for home consumption, and they now face warming climates and more erratic rainfall that further reduce yields. At the same time, their typical storage practices, which include polypropylene bags with or without insecticides, do not protect well enough against the main storage pests (García-Lara et al., 2019), resulting in losses as high as 60% of stored grain (Odjo et al., 2020). Many studies document the value of improved storage practices for smallholders' food security and nutrition (Brown et al., 2015; Kumar and Kalita, 2017; Tefera, 2012) and, particularly, the effectiveness of hermetic storage technologies in minimizing insect and fungi damage (Abass et al., 2018; Chigoverah and Mvumi, 2016; De Groot et al., 2013; Odjo et al., 2020).

Previous studies also documented storage technology effects on seed viability or visible quality attributes, but there has been little to assess the impact of storage practices on grain quality and nutritional losses (Affognon et al., 2015; Nkhata et al., 2021; Taleon et al., 2017). Further, the few published studies on this topic in Mexico were conducted at single locations, whereas Mexico is characterized by numerous, highly diverse maize farming agro-ecologies (García-Lara et al., 2019). García Leños et al. (2007) reported a 15% decrease in germination for seed stored for six months in hermetic metal silos, compared to a 50% loss under conventional practices, at a single location in the state of Guanajuato, Mexico. According to García-Lara et al. (2020), hermetic storage better maintained grain composition (starch, protein, oil, fiber, and ash content), physical parameters (moisture content, test weight, flotation index and thousand kernel weight) and tortilla-making quality, compared with polypropylene bags, in the state of Mexico, Mexico.

Stathers et al. (2020) recorded that insect infestation can lead to some chemical changes in damaged grains, including a decrease in carbohydrate content and a subsequent weight loss. As visibly damaged grain is generally eliminated through winnowing before consumption, the effect of storage conditions on the remaining grain quality attributes requires further investigation.

Odjo et al. (2020) reported insect and fungi damage and live insect numbers in stored maize, in controlled experiments led by researchers

and side-by-side comparisons managed by extension agents with farmers, over two years. The results showed that polypropylene bags, the most common farmer's storage practice, failed to minimize losses, with grain weight loss reaching 11.4% in tropical conditions after six months of storage. Insect damage with farmer's conventional storage technologies was ten times higher in the lowlands than in the highlands, while hermetic technologies minimized losses regardless of storage conditions with less than 4% of insect-damaged grain.

The current study presents grain and seed quality data collected from the controlled experiments reported by Odjo et al. (2020). Samples were analyzed to (1) compare the efficacy of storage technologies in maintaining grain and seed quality attributes of grain without apparent damage, (2) evaluate the effect of weather conditions on that efficacy, and (3) assess the relationship between storage conditions, grain characteristics, grain damage, and grain and seed quality parameters.

2. Materials and methods

2.1. Description of experiments

In 2017 and 2018 the International Maize and Wheat Improvement Center (CIMMYT) and its collaborators in Mexico conducted storage experiments at six sites from 36 to 2282 m above sea level (masl) and in temperate, tropical savanna and tropical humid conditions (Table 1; supplementary Fig. B1). The sites are located in important rainfed farming areas for maize and other grains, operated chiefly by smallholders (Fonteyne et al., 2021).

At each site, a comparison was made between (1) conventional storage technologies (commonly used by farmers) and innovative storage technologies selected from (2) hermetic technologies, (3) alternative conditioning agents and (4) alternative hermetic technologies. Conventional storage technologies included polypropylene bag (PP), polypropylene bag with aluminum phosphide (PP_AP) at a dosage of 1 tablet per 50 kg (one tablet weighs approximately 3 g and contains 56% aluminum phosphide). Hermetic technologies included hermetic metal silos (HMS), the GrainPro Hermetic SuperGrainbag® Farm, a hermetic bag with a tie-down system (HBT) and the GrainPro Hermetic SuperGrainbag® Premium RZ, a hermetic bag with a zip system (HBZ). Alternative conditioning agents include polypropylene bags with standard lime (PP_SL) and polypropylene bags with micronized lime (PP_ML), both at a dosage of 4 kg per ton. Alternative hermetic technologies include plastic bottles (PBO) and silage plastic bags (SPB). The storage technologies were chosen together with local collaborators, depending on their interest, the locally used practices as well as storage technologies commercially available, so they were not always the same in both years (Table 1). Odjo et al. (2020) describes these storage technologies (see also supplementary Fig. B2) and additional details on experimental conditions, the technologies evaluated and postharvest parameters including moisture content, temperature and grain damage. Depending on the grain available, local collaborators provided a native or a hybrid maize variety to use in the experiment. A total of 8 hybrid and 4 native varieties were evaluated; 10 of the varieties were of white maize and two were yellow (Table 1).

In each experiment, researchers randomly collected three representative maize samples using hand scoops before filling the storage containers and stores at -18°C . After six months storage, three samples were collected from the top, middle and bottom of each container. Samples were manually cleaned and screened by trained CIMMYT staff using sieves with a 2.5 mm mesh. Approximately 1 kg of maize kernels, without apparent insect, fungi or rodent damage was further analyzed for grain quality parameters. As farmers in Mexico carefully select their grain for food and seed based on visual aspects such as kernel color and visible damage by insects or fungi (Latournerie Moreno et al., 2006; Tuxill et al., 2010), only maize kernel samples without apparent damage were analyzed (see supplementary Fig. B3 for grain description and pictures). As reported by Odjo et al. (2020), damage was generally less at

sites above 2000 masl and undamaged grain constituted more than 80% of samples except in Zacualtipán, where a high density of live insects was recorded (Table 2). At sites below 500 masl, hermetic technologies generally maintained a higher percentage of grain without damage while a high percentage of damaged grain was recorded with non-hermetic storage technologies (Table 2). In three experiments (Zacualtipán 2017, Pochutla 2017, Pochutla 2018), initial samples were lost, while in two cases (Pochutla 2018 and Palacios-Rojas, 2018), it was not possible to obtain sufficient grain without apparent damage for laboratory analysis for PP_SL and PP, so these samples were not included in the study reported here.

2.2. Grain and seed quality analysis

2.2.1. Grain chemical and physical composition

Both initial samples (defrosted over one night at room temperature) and collected samples were analyzed in the “Evangalina Villegas” Maize Quality Laboratory of CIMMYT, Mexico, following the laboratory’s standard procedure (Palacios-Rojas, 2018) with two analytical repetitions per sample (three samples per storage technology). All reagents used were of analytical grade and all results are expressed on a dry basis.

The first series of analyses were performed on whole grain. Starch, protein, and oil contents of grain were estimated by near-infrared spectroscopy using a FOSS Infratec™ 1241 Grain Analyser (Denmark) with the manufacturer’s calibrations. Hundred kernel weight was determined by weighing in duplicate 100 randomly selected grains per sample (Palacios-Rojas, 2018; Serna-Saldivar, 2012).

Flotation index is an indirect parameter of grain hardness and is used in Mexico as an indicator of nixtamalization (alkaline cooking) quality;

samples with a high flotation index tend to have lower tortilla yields. This parameter was estimated by counting the number of floating grains after mild stirring to the right three times and to the left three times of 100 grains in a sodium nitrate solution with a specific density of 1.25 g mL⁻¹. Color was measured using a portal Minolta CR-410 colorimeter (Konica Minolta, Japan) as an indicator of grain acceptance and preference. The L*a*b* color space of the International Commission on Illumination (CIE) was used for color evaluation. The L-scale represents lightness, from 0 (darkest) to 100 (lightest); the a-scale represents redness, with negative value for green and positive value for red; and the b-scale represents yellowness, with negative value for blue and positive value for yellow. Values obtained were used to calculate a total color difference (ΔE^*), which represents the difference of color values between initial samples and samples obtained after storage. It was computed as per Wrolstad and Smith (2010) with the following equation (1):

$$\Delta E^* = \sqrt{(L_s^* - L_i^*)^2 + (a_s^* - a_i^*)^2 + (b_s^* - b_i^*)^2} \quad (1)$$

where s represents the value for the color parameter of the sample measured after storage, and i represents the value of the same color parameter for the sample collected at the beginning of the experiment.

The second series of analyses was performed on maize flour obtained from collected samples without apparent damage, both initial samples and those taken after storage with a Twister Cyclone Mill (Retsch, Germany) using a 0.5 mm mesh. Bound phenolic compounds of grain, total ferulic acids and p-coumaric acid, were estimated for the maize flour as described by Muzhingi et al. (2017) after precipitation with an 80% ethanol solution, hydrolysis with a 2 mol L⁻¹ sodium hydroxide

Table 1

Sites of experiments, maize variety characteristics (mean \pm standard deviation) and storage technologies evaluated in each experiment in 2017 and 2018.

| Parameters | Sites of experiments | | | | | | | | | | | |
|--|-----------------------------|---------------------------------|-----------------------------|----------|-------------|--------|------------------------------|-------------------------------|-----------------------------|-------------------------------|-------------------------------|---------------|
| | Texcoco | | Yanhuitlán | | Zacualtipán | | Pochutla | | Cotzacón | | Peto | |
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Site characteristics | | | | | | | | | | | | |
| Elevation | 2282 masl | | 2138 masl | | 2070 masl | | 202 masl | | 113 masl | | 36 masl | |
| Climate | Temperate | | Temperate | | Temperate | | Tropical savanna | | Tropical savanna | | Tropical humid | |
| Year | | | | | | | | | | | | |
| Maize varieties evaluated | | | | | | | | | | | | |
| Name of variety | HC-8 (Aspros, Mexico) | Albatros (Asgrow, Mexico) | Ares (Unisem, Mexico) | Jaltepec | na | na | H-565 (Inifap, Mexico) | VS-536 (Inifap, Mexico) | 7575 (Asgrow, Mexico) | Nv 15 (Novasem, Mexico) | Dk-390 (Dekalb, Mexico) | Tsit bacal |
| Type of variety | Hybrid | Hybrid | Hybrid | Native | Native | Native | Hybrid | Hybrid | Hybrid | Hybrid | Hybrid | Native |
| Color | White | White | White | White | White | Yellow | White | White | White | White | White | Yellow |
| Conventional storage technology evaluated | | | | | | | | | | | | |
| Polypropylene bag (PP) | X | X | | | X | X | | | | | X | X |
| PP with aluminum phosphide tablet (PP_AP) | | | X | X | | | X | | X | X | | |
| PP with standard lime (PP_SL) | | | | | | | | X | | | | |
| Other storage technologies evaluated | | | | | | | | | | | | |
| PP with micronized lime (PP_ML) | X | | | | | | | | X | | X | X |
| Silage plastic bag (SPB) | | | | | | | | | X | | | |
| Plastic bottle (PBO) | | X | | | | | | X | | X | | X |
| GrainPro hermetic SuperGrainbag® Farm (HBT) | | | X | X | X | | X | X | X | X | | X |
| GrainPro hermetic SuperGrainbag® Premium RZ with zip (HBZ) | X | X | | | | X | | | | | X | |
| Hermetic metal silo (HMS) | X | X | X | X | X | X | X | X | X | X | X | X |

X: sites where the storage technology was evaluated; na: not available; masl: m above sea level; N: number of repetitions; L*: CIE color scale representing lightness; a*: CIE color scale representing redness; b*: CIE color scale representing yellowness.

Table 2
Percentage of non-damaged grain at experimental sites (mean \pm standard error; $N = 3$).

| Parameters (elevation) | Texcoco (2282 masl) | | Yanhuitlán (2138 masl) | | Zacualtipán (2070 masl) | | Pochutla (202 masl) | | Cotzacón (113 masl) | | Peto (36 masl) | |
|------------------------|---------------------|-----------------|------------------------|-----------------|-------------------------|-----------------|---------------------|-----------------|---------------------|-----------------|-----------------|-----------------|
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| PP | 91.9 \pm 0.17 | 90.8 \pm 1.18 | 93.8 \pm 0.40 | | | 62.6 \pm 5.98 | | | | | 75.5 \pm 3.43 | 25.0 \pm 3.04 |
| PP_AP | | | 91.8 \pm 0.85 | 80.8 \pm 0.86 | | | 81.8 \pm 1.94 | | 39.1 \pm 8.34 | 90.4 \pm 0.22 | | |
| PP_SL | | | | | | | 96.8 \pm 0.29 | 57.5 \pm 8.17 | | | | |
| PP_ML | 90.6 \pm 0.81 | | | | | | | | 74.1 \pm 4.67 | | 92.0 \pm 1.05 | 67.2 \pm 8.24 |
| SPB | | | | | | | | | | 92.0 \pm 0.04 | | |
| PBO | | 95.2 \pm 0.45 | | | | | | | 87.0 \pm 1.42 | 91.1 \pm 0.43 | | 97.0 \pm 1.31 |
| HBT | | | 91.3 \pm 0.62 | 85.2 \pm 1.61 | 75.1 \pm 1.37 | | 97.7 \pm 0.08 | 89.4 \pm 1.18 | 90.1 \pm 0.37 | 94.4 \pm 0.46 | | 96.5 \pm 0.18 |
| HBZ | 91.5 \pm 0.44 | 95.3 \pm 0.10 | | | | 67.1 \pm 2.83 | | | | | 94.3 \pm 0.12 | |
| HMS | 92.9 \pm 0.08 | 94.6 \pm 0.52 | 90.5 \pm 0.77 | 85.9 \pm 0.23 | 71.8 \pm 3.75 | 65.1 \pm 7.30 | 97.8 \pm 0.12 | 87.8 \pm 1.28 | 85.8 \pm 1.33 | 89.1 \pm 0.51 | 95.1 \pm 0.71 | 92.5 \pm 0.64 |

N: number of repetitions; PP: polypropylene bag; PP_AP: polypropylene bag with aluminum phosphide tablet; PP_SL: polypropylene bag with standard lime (calcium hydroxide); PP_ML: polypropylene bag with micronized lime (calcium hydroxide); SPB: silage plastic bag; PBO: plastic Bottle; HBT: GrainPro hermetic SuperGrainbag® Farm; HBZ: GrainPro hermetic SuperGrainbag® Premium RZ with zip; HMS: hermetic metal silo.

solution, extraction with a solution of ethyl acetate (1:1 v/v), separation and quantification using a gallic acid solution (100 $\mu\text{g mL}^{-1}$) as an internal standard, and an HPLC system composed of a Waters 2695 pump, a Waters 2996 PDA detector and the UV-visible detector set at a wavelength of 280 nm. The detection limit for both ferulic acid and p-coumaric acid was 0.01 $\mu\text{g mL}^{-1}$, while the limit of quantification was 0.02 $\mu\text{g mL}^{-1}$ (Palacios-Rojas, 2018). Ether extract was determined using petroleum ether with a Soxtec 2050 system (FOSS, Denmark), as a measure of crude fat content. Fat acidity reflects biochemical changes during storage and its increase indicates hydrolysis of triglycerides as a result of poor storage conditions. Fat acidity was determined after a toluene extraction and titration with a 0.0178 mol L⁻¹ solution of potassium hydroxide (KOH) and was expressed in mg of KOH per 100 g of dry flour.

2.2.2. Seed germination analysis

Germination tests were performed using the rolled paper towel seed germination test of CIMMYT as per Warham et al. (1996). Fifty seeds were randomly selected and placed on the upper halves of moist filter or blotter paper towels (50 \times 25 cm) and incubated in a seed incubator at 90% relative humidity, with alternating 12 h at 30 °C in light and 12 h at 20 °C in the dark, for 7 days based on the recommendation of the 1985 rules of the International Seed Testing Association (ISTA). Germinated grains were visually checked every day and “normal seedlings” counted, indicating that these seeds have potential for development of plants when grown in good soil under optimum conditions. Germinated seeds and normal seedlings were expressed as a percentage.

2.3. Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics 21 as suggested by Field (2005). Descriptive statistics such as mean, standard errors and coefficient of variation (CV) of samples from the same experiment were used to summarize the data. The effect of storage technologies on grain and seed quality characteristics was initially studied for each experimental site, comparing the differences between the grain's initial characteristics and the characteristics after six months of storage under different technologies using a one-way analysis of variance (ANOVA). Initial samples of the grain before storage were included in the model as a “storage technology”. Each storage technology was compared with the initial values using a two-side Dunnett test. In the case of the total color difference parameter, where there is no initial value, a Fisher protected *t*-test was used to compare samples from different storage technologies. A *P*-value of <0.05 was used to determine significant differences.

Data from the same experiments already published by Odjo et al. (2020) were combined with data collected in the present study to analyze the relationship between storage conditions, grain damage and grain and seed quality parameters. Data considered includes: (1)

environmental parameters at the experiment sites (elevation, monthly average minimum and maximum temperature and minimum and maximum relative humidity); (2) postharvest loss parameters (percentages of insect-damaged grain, fungi-damaged grain, total damaged grain, weight loss, numbers of live maize weevils *Strophilus zeamais* Motschulsky (Coleoptera: Curculionidae) and live large grain borers *Prostephanus truncatus* Horn (Coleoptera: Bostrichidae), and (3) grain and seed quality parameters (percentages of germination and of normal seedlings, and data for ether extract, fat acidity, hundred kernel weight, flotation index, total ferulic acid and p-coumaric acid contents, and total color difference). The relationship between these parameters were analyzed through Spearman's correlation. Partial correlations were also computed to examine the relationships between grain characteristics, postharvest loss parameters, and grain and seed quality parameters, by controlling experiments (site and year) and the environmental parameters as conditions varied from site to site and from year to year.

3. Results

3.1. Impact of storage technologies on seed quality

Post-storage seed germination varied from 2 to 100%, depending on the storage practice, while the percentage of normal seedlings varied between 0% (polypropylene bag with micronized lime in Peto 2018) and 94% (hermetic metal silo in Yanhuitlán 2017, Table 3). Overall, there was no significant difference in germination percentages before or after storage, at sites above 2000 masl (Texcoco, Yanhuitlán, Zacualtipán), except for Zacualtipán 2018, where seed germination decreased after storage in polypropylene bags. There were significant differences at sites below 500 masl, particularly with grain stored using non-hermetic technologies. Across sites below 500 masl and over the two years of the study, storage in non-hermetic containers led to a 56% decrease in seed germination (polypropylene bags with and without conditioning agents). In contrast, germination of seeds stored using hermetic technologies (metal silos or hermetic bags) showed an average decrease in germination of only 2.8%. For locations where the initial sample was not available, the percentage of seed germination for samples under hermetic storage was higher overall than that of samples stored using non-hermetic technologies (Table 3). Alternative hermetic technologies, including plastic bottles, were also effective in maintaining seed germination levels.

The percentage of normal seedlings followed the same trend as for seed germination. Overall, there was no significant difference in normal seedlings rate between initial samples and samples stored using conventional hermetic technologies (hermetic metal silos and hermetic bags) or alternative hermetic technologies (silage plastic bags and plastic bottles). In contrast, there was a significant decrease in the percentage of normal seedlings from samples that had been stored using non-hermetic technologies, particularly for sites below 500 masl.

Table 3
Effect of storage technologies on percentages of germination and normal seedlings, after six months of storage at different experimental sites (mean ± standard error).

| Parameters (elevation) | Texcoco (2282 masl) | | Yanhuitlán (2138 masl) | | Zacualtipán (2070 masl) | | Pochutla (202 masl) | | Cotzacoán (113 masl) | | Peto (36 masl) | |
|---------------------------|---------------------|------------|------------------------|-------------|-------------------------|------------|---------------------|------------|----------------------|-------------|----------------|------------|
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Germination (%): N=3 | | | | | | | | | | | | |
| Initial sample | 90.0±4.00* | 97.7±1.33* | na | 97.3±0.67* | 86.0±2.31* | 85.7±1.20* | na | na | 88.7±0.67* | 94.7±0.67* | 99.3±0.67* | 97.3±0.67* |
| PP | 88.7±2.91* | 94.7±0.88* | 97.3±0.67 | 86.7±4.06* | 52.3±6.57* | | | | | | 69.3±8.35* | ns |
| PP_AP | | | | | | | 66.7±1.76 | | 18.0±6.11* | 55.0±11.00* | | |
| PP_SL | | | | | | | 74.7±3.33 | ns | | | | |
| PP_ML | 86.7±1.33* | | | | | | | | 22.0±11.02* | | 65.3±6.57* | 2.0±1.15* |
| SPB | | | | | | | | | | 87.3±1.33* | | |
| PBO | | 96.3±0.88* | | | | | | 68.0±6.00 | | 94.0±3.06* | | 99.7±0.33* |
| HBT | | | 98.0±1.15* | 93.3±2.40* | 96.7±2.40* | | 95.3±0.33 | 59.3±14.25 | 88.7±0.67* | 89.3±2.40* | | 98.0±0.00* |
| HBZ | 86.0±2.00* | 95.3±0.33* | | | | 88.7±1.20* | | | | | 95.7±0.33* | |
| HMS | 83.3±2.91* | 96.3±1.45* | 100±0.00 | 93.3±2.40* | 91.3±2.91* | 84.3±1.45* | 94.7±0.88 | 42.0±2.00 | 77.3±5.70* | 94.0±2.31* | 98.0±2.00* | 98.7±0.67* |
| CV (%) | 5.42 | 1.95 | 1.53 | 6.06 | 6.57 | 20.89 | 18.00 | 31.38 | 58.41 | 15.40 | 19.72 | 50.47 |
| P | 0.525 | 0.380 | 0.150 | 0.112 | 0.068 | <0.001 | <0.001 | 0.196 | <0.001 | <0.001 | <0.001 | <0.001 |
| Normal seedlings (%): N=3 | | | | | | | | | | | | |
| Initial sample | 80.0±5.03* | 88.0±1.00* | na | 87.3±2.40* | 70.7±2.91* | 62.7±1.20* | na | na | 77.3±3.33* | 72.0±4.16* | 88.7±1.33* | 90.7±1.33* |
| PP | 78.7±2.40* | 83.3±5.70* | 83.3±0.67 | | | 33.7±8.17* | | | | | 46.0±10.00* | ns |
| PP_AP | | | 90.7±1.33 | 56.7±13.78* | | | 30.0±1.76 | | 4.0±1.15* | 37.0±9.00* | | |
| PP_SL | | | | | | | 46.0±3.33 | ns | | | | |
| PP_ML | 70.0±3.06* | | | | | | | | 10.0±5.29* | | 43.3±6.57* | 0 |
| SPB | | | | | | | | | | 52.0±5.21* | | |
| PBO | | 87.7±0.33* | | | | | | 46.0±3.45 | | 66.7±1.76* | | 94.0±1.15* |
| HBT | | | 88.7±1.76 | 72.7±9.61* | 87.3±3.71* | | 88.7±4.37 | 40.0±12.22 | 42.0±5.29* | 67.3±2.67* | | 91.3±1.33* |
| HBZ | 74.7±1.76* | 85.0±1.73* | | | | 65.0±3.21* | | | | | 87.3±0.67* | |
| HMS | 70.7±4.06* | 82.7±2.73* | 91.3±1.76 | 76.0±2.31* | 75.3±7.06* | 56.0±1.53* | 86.7±1.76 | 22.0±0.00 | 44.7±6.96* | 68.0±4.16* | 92.0±4.00* | 90.0±2.00* |
| CV (%) | 8.80 | 5.74 | 4.43 | 23.32 | 13.45 | 26.76 | 43.06 | 42.85 | 79.65 | 21.24 | 33.86 | 51.86 |
| P | 0.224 | 0.624 | 0.017 | 0.167 | 0.120 | 0.004 | <0.001 | 0.131 | <0.001 | 0.003 | <0.001 | <0.001 |

N: number of repetitions; PP: polypropylene bag; PP_AP: polypropylene bag with aluminum phosphide tablet; PP_SL: polypropylene bag with standard lime (calcium hydroxide); PP_ML: polypropylene bag with micronized lime (calcium hydroxide); SPB: silage plastic bag; PBO: plastic Bottle; HBT: GrainPro hermetic SuperGrainbag® Farm; HBZ: GrainPro hermetic SuperGrainbag® Premium RZ with zip; HMS: hermetic metal silo. P: p-value of the overall mean; different letters within the same column indicate statistically significant differences from the initial sample obtained with the Dunnett's test (P < 0.05); CV: coefficient of variation of samples from the same experiment; na: not available; ns: no sufficient grain without apparent damage; grey area indicates that the technology was not tested at the corresponding site and year.

3.2. Impact of storage technologies on grain chemical and physical parameters

The evaluated storage technologies had little impact on the starch, protein or oil contents of grain, compared with initial samples: the coefficients of variation of these parameters were less than 5% over experiments (supplementary table A2). The coefficient of variation of p-coumaric acid and total ferulic acid was between 6.4% and 24.1% and

6.2% and 24.3% of the experiments, respectively (supplementary table A3). There were significant differences in those parameters for pre- and post-storage samples, for those parameters even if no clear trend appeared.

Ether extract values were similar across years and sites, with coefficient of variation of between 3.8% and 10.4% (Table 4). There were significant increases in fat acidity between initial and stored samples, for grains stored using polypropylene bags, polypropylene bags with

Table 4
Effect of storage technologies on ether extracts (%) and fat acidity (mg of KOH/100g) after six months of storage at different experimental sites (mean ± standard error).

| Parameters (elevation) | Texcoco (2282 masl) | | Yanhuitlán (2138 masl) | | Zacualtipán (2070 masl) | | Pochutla (202 masl) | | Cotzacoán (113 masl) | | Peto (36 masl) | |
|-----------------------------------|---------------------|-----------|------------------------|------------|-------------------------|------------|---------------------|-----------|----------------------|-----------|----------------|------------|
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Ether extract (%): N=3 | | | | | | | | | | | | |
| Initial sample | 4.2±0.06* | 4.3±0.15* | na | 4.5±0.27* | 4.6±0.19* | 4.4±0.23* | na | na | 4.3±0.28* | 4.5±0.13* | 4.0±0.16* | 4.3±0.14* |
| PP | 4.0±0.06* | 3.8±0.26* | 4.2±0.07 | | | 4.4±0.24* | | | | | 4.2±0.17* | ns |
| PP_AP | | | 4.2±0.14 | 4.2±0.16* | | | 4.4±0.09 | | 4.6±0.38* | 4.2±0.32* | | |
| PP_SL | | | | | | | 4.4±0.15 | ns | | | | |
| PP_ML | 4.1±0.23* | | | | | | | | 4.4±0.12* | | 4.6±0.11* | 4.1±0.06* |
| SPB | | | | | | | | | | 4.1±0.13* | | |
| PBO | | 3.8±0.16* | | | | | | 3.8±0.07 | | 4.0±0.18* | | 4.3±0.16* |
| HBT | | | 4.2±0.15 | 4.2±0.18* | 4.7±0.06* | | 4.4±0.07 | 4.1±0.31 | 4.7±0.07* | 4.2±0.08* | | 4.2±0.14* |
| HBZ | 4.0±0.02* | 4.7±0.24* | | | | 4.0±0.27* | | | | | 4.4±0.03* | |
| HMS | 4.0±0.11* | 4.2±0.16* | 4.1±0.08 | 4.6±0.22* | 4.8±0.03* | 3.9±0.09* | 4.5±0.12 | 3.7±0.01 | 5.0±0.12* | 4.2±0.05* | 4.4±0.08* | 3.9±0.11* |
| CV (%) | 4.95 | 10.39 | 4.20 | 8.29 | 4.16 | 9.13 | 3.79 | 8.86 | 9.11 | 6.51 | 6.95 | 5.98 |
| P | 0.583 | 0.072 | 0.964 | 0.486 | 0.470 | 0.418 | 0.979 | 0.264 | 0.251 | 0.187 | 0.024 | 0.147 |
| Fat acidity (mg of KOH/100g): N=3 | | | | | | | | | | | | |
| Initial sample | 12.6±1.05* | 7.0±0.17* | na | 11.2±0.67* | 20.5±1.21* | 10.2±0.58* | na | na | 14.0±0.74* | 5.7±0.72* | 4.0±0.63* | 6.7±0.40* |
| PP | 15.6±1.16* | 9.3±0.64* | 9.6±0.42 | | | 13.4±0.87* | | | | | 9.8±0.37* | ns |
| PP_AP | | | 11.0±1.32 | 14.2±2.21* | | | 11.3±0.40 | | 20.3±0.25* | 5.0±0.66* | | |
| PP_SL | | | | | | | 7.8±0.21 | ns | | | | |
| PP_ML | 21.2±1.64* | | | | | | | | 20.8±1.39* | | 8.7±0.52* | 52.1±3.34* |
| SPB | | | | | | | | | | 4.8±0.68* | | |
| PBO | | 8.2±0.16* | | | | | | 11.1±2.53 | | 4.7±1.29* | | 5.5±0.49* |
| HBT | | | 5.9±0.34 | 10.2±2.08* | 7.7±0.26* | | 7.0±0.24 | 13.8±3.82 | 16.8±2.57* | 4.8±0.33* | | 6.7±0.32* |
| HBZ | 20.1±1.10* | 6.1±0.47* | | | | 14.8±1.38* | | | | | 7.5±0.10* | |
| HMS | 21.7±1.73* | 6.7±0.57* | 5.9±0.94 | 13.6±4.76* | 14.2±2.54* | 13.4±0.52* | 6.5±0.19 | 15.2±2.70 | 11.9±0.44* | 5.8±0.62* | 8.9±0.35* | 7.4±0.63* |
| CV (%) | 22.94 | 18.38 | 33.18 | 36.91 | 42.83 | 17.10 | 24.41 | 36.92 | 24.63 | 23.34 | 28.03 | 121.11 |
| P | 0.003 | 0.003 | 0.005 | 0.732 | 0.004 | 0.037 | <0.001 | 0.660 | 0.003 | 0.868 | <0.001 | <0.001 |

N: number of repetitions; PP: polypropylene bag; PP_AP: polypropylene bag with aluminum phosphide tablet; PP_SL: polypropylene bag with standard lime (calcium hydroxide); PP_ML: polypropylene bag with micronized lime (calcium hydroxide); SPB: silage plastic bag; PBO: plastic Bottle; HBT: GrainPro hermetic SuperGrainbag® Farm; HBZ: GrainPro hermetic SuperGrainbag® Premium RZ with zip; HMS: hermetic metal silo. P: p-value of the overall mean; different letters within the same column indicate statistically significant differences from the initial sample obtained with the Dunnett's test (p < 0.05); CV: coefficient of variation of samples from the same experiment; na: not available; ns: no sufficient grain without apparent damage; grey area indicates that the technology was not tested at the corresponding site and year.

aluminum phosphide and polypropylene bags with micronized lime. For grain stored using hermetic technologies, there were cases where the level of fat acidity did not change and some where they increased. In places where the initial samples were not available, samples stored hermetically had lower fat acidity than those stored using non-hermetic technologies. As a general trend, hermetic storage technologies preserved maize fat acidity, while samples stored using non-hermetic storage technologies were more prone to fat oxidation.

The hundred kernel weight varied between 16.8 g and 42.0 g for all samples with lower values for maize varieties from sites below 500 masl (Table 5). However, there was less variation among samples from the same experiment (coefficients of variation between 1.8% and 9.7%). The flotation index ranged from 4.5 to 75.3 and was significantly influenced by storage technology (Table 5). Overall, grain stored using hermetic technologies had lower flotation index values.

Coefficients of variation for color parameters L*, a* and b* varied between 1.4 and 3.6%, 6.4 and 18.8% and 2.1 and 12.4% respectively (supplementary table A4). Significant increases in total color difference were observed after storage for polypropylene bags with standard lime and polypropylene bags with micronized lime. The total color difference was higher overall for sites below 500 masl than above 2000 masl. At all sites, grain color was less affected over time for samples stored using hermetic technologies (Table 6).

3.3. Relationship among environmental parameters, postharvest loss parameters, and grain and seed quality parameters

The matrix of Spearman coefficient of correlation (ρ) showed significant but low correlations among environmental parameters, post-harvest loss parameters, and grain and seed quality parameters (supplementary table A5). Among the highest values, the hundred kernel weight was negatively correlated with the average minimum and maximum temperatures ($\rho = -0.71, P < 0.001; \rho = -0.59, P < 0.001$, respectively) as well as grain temperature ($\rho = -0.66, P < 0.001$) while positively correlated with site elevation ($\rho = 0.67, p < 0.001$). The percentage of total damaged-grain was negatively correlated with the

percentage of normal seedlings, germination, fat acidity and flotation index ($\rho = -0.59, P < 0.001; \rho = -0.54, P < 0.001; \rho = -0.55, P < 0.001, \rho = -0.58, P < 0.001$, respectively).

Partial correlations controlling experiments and environmental parameters, were significant and higher (Table 7). Grain moisture content was negatively correlated with the percentage of normal seedlings and positively correlated with fat acidity and flotation index, while grain temperature was negatively correlated with hundred kernel weight and flotation index. Postharvest loss parameters (percentages of fungi- or insect-damaged, weight loss, total damaged grain, and number of live *S. zeamais* and *P. truncatus*) were negatively correlated with seed quality parameters and positively correlated with fat acidity and flotation index (Table 7).

4. Discussion

This is the first study that compiles data on maize grain and seed quality loss in different Mexican maize agro-ecologies for storage practices. Odjo et al. (2020) demonstrated at the same sites that storing grain in non-hermetic technologies resulted in a high percentage of quantitative loss in lowland conditions, while damage was less significant in the highlands. Grain damage frequently affects grain quality, market grades, and prices (Hodges et al., 2011; Stathers et al., 2020), requiring farmers to winnow and clean before marketing or preparing food. This study assessed whether decreased grain and seed quality go beyond visible damage, analyzing samples of visually undamaged grain and seed, collected from different storage technologies.

Data presented here varied among experiments due to varying conditions (elevation and other environmental factors, varieties used). Storing seed in non-hermetic containers substantially decreased its viability, particularly at sites below 500 masl. Similarly, in on-farm experiments in Tanzania, germination rates decreased by around 40% for seed stored for 30 weeks in polypropylene bags (Abass et al., 2018). In contrast, there was no significant reduction in germination for seeds stored using hermetic technologies or alternative hermetic technologies. The reduction in germination capacity is associated with poor storage

Table 5
Effect of storage technologies on hundred kernel weight (g) and flotation index after six months of storage at different experimental sites (mean \pm standard error).

| Parameters (elevation) | Texcoco (2282 masl) | | Yanhuitlán (2138 masl) | | Zacualtipán (2070 masl) | | Pochutla (202 masl) | | Cotzacón (113 masl) | | Peto (36 masl) | |
|--------------------------------|------------------------------|------------------------------|------------------------|------------------------------|------------------------------|------------------------------|---------------------|-----------------|------------------------------|------------------------------|------------------------------|-------------------------------|
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Hundred kernel weight (g): N=3 | | | | | | | | | | | | |
| Initial sample | 35.1 \pm 0.33 ^a | 33.6 \pm 0.23 ^a | na | 42.0 \pm 0.40 ^a | 26.4 \pm 0.14 ^a | 30.7 \pm 0.41 ^a | na | na | 28.0 \pm 0.50 ^a | 28.1 \pm 0.25 ^a | 29.9 \pm 0.32 ^a | 17.1 \pm 0.33 ^a |
| PP | 34.2 \pm 0.07 ^a | 33.0 \pm 0.51 ^a | 30.3 \pm 0.12 | 40.7 \pm 0.79 ^a | | 29.5 \pm 0.25 ^a | | | | | 27.7 \pm 0.50 ^a | ns |
| PP_AP | | | | | | | 23.9 \pm 0.55 | | 29.8 \pm 1.94 ^a | 27.9 \pm 0.38 ^a | | |
| PP_SL | | | 30.1 \pm 0.67 | | | | 24.0 \pm 0.49 | ns | | | | |
| PP_ML | 33.7 \pm 0.37 ^b | | | | | | | | 31.1 \pm 0.72 ^a | | 29.8 \pm 0.06 ^a | 16.8 \pm 0.15 ^a |
| SPB | | | | | | | | | | | 30.0 \pm 0.17 ^b | |
| PBO | | 32.8 \pm 0.32 ^a | | | | | | 31.8 \pm 0.79 | | | 29.1 \pm 0.18 ^a | 19.1 \pm 0.19 ^b |
| HBT | | | 30.2 \pm 0.31 | 36.4 \pm 0.92 ^b | 24.9 \pm 0.28 ^b | | 24.1 \pm 0.25 | 31.5 \pm 2.64 | 28.2 \pm 0.86 ^a | 28.8 \pm 0.79 ^a | | 18.5 \pm 0.33 ^b |
| HBZ | 34.1 \pm 0.18 ^a | 32.6 \pm 0.21 ^a | | | | 31.3 \pm 1.37 ^a | | | | | 28.6 \pm 0.77 ^a | |
| HMS | 34.4 \pm 0.32 ^a | 32.5 \pm 0.55 ^a | 29.4 \pm 0.46 | 38.3 \pm 1.42 ^b | 24.5 \pm 0.37 ^b | 29.8 \pm 0.62 ^a | 23.2 \pm 0.54 | 28.5 \pm 0.96 | 29.2 \pm 1.46 ^a | 27.0 \pm 0.12 ^a | 29.0 \pm 0.21 ^a | 18.4 \pm 0.14 ^b |
| CV (%) | 1.83 | 2.07 | 2.52 | 6.76 | 3.77 | 4.58 | 3.35 | 9.73 | 7.24 | 3.97 | 3.71 | 5.47 |
| P | 0.051 | 0.422 | 0.444 | 0.013 | 0.007 | 0.397 | 0.554 | 0.373 | 0.432 | 0.003 | 0.028 | <0.001 |
| Flotation index: N=3 | | | | | | | | | | | | |
| Initial sample | 53.7 \pm 3.53 ^a | 14.8 \pm 0.88 ^a | na | 50.5 \pm 0.76 ^a | 49.8 \pm 3.56 ^a | 64.7 \pm 3.49 ^a | na | na | 50.0 \pm 3.04 ^a | 15.5 \pm 1.89 ^a | 4.5 \pm 0.76 ^a | 30.8 \pm 2.60 ^a |
| PP | 56.3 \pm 1.33 ^a | 10.3 \pm 1.17 ^a | 18.5 \pm 0.87 | | | 75.3 \pm 0.67 ^b | | | | | 34.3 \pm 9.41 ^a | ns |
| PP_AP | | | 21.7 \pm 3.59 | 59.5 \pm 1.00 ^a | | | 49.7 \pm 1.59 | | 82.7 \pm 1.30 ^b | 21.0 \pm 0.00 ^b | | |
| PP_SL | | | | | | | 43.7 \pm 3.93 | ns | | | | |
| PP_ML | 61.7 \pm 1.76 ^a | | | | | | | | 79.5 \pm 2.50 ^b | | 30.0 \pm 4.27 ^b | 65.3 \pm 1.01 ^b |
| SPB | | | | | | | | | | | | |
| PBO | | 10.3 \pm 0.88 ^a | | | | | | | | | | |
| HBT | | | 17.2 \pm 2.05 | 71.5 \pm 6.75 ^b | 29.3 \pm 1.92 ^b | | 26.8 \pm 1.64 | 49.0 \pm 2.65 | 58.8 \pm 6.33 ^a | 14.7 \pm 1.01 ^a | | 43.8 \pm 16.61 ^a |
| HBZ | 55.3 \pm 2.73 ^a | 11.3 \pm 1.76 ^a | | | | 66.0 \pm 2.75 ^a | | | | | 16.8 \pm 2.89 ^a | |
| HMS | 58.3 \pm 3.18 ^a | 12.5 \pm 2.93 ^a | 16.8 \pm 1.59 | 53.8 \pm 1.45 ^a | 35.5 \pm 1.32 ^b | 70.3 \pm 2.33 ^a | 30.0 \pm 4.80 | 54.5 \pm 4.37 | 60.0 \pm 6.26 ^a | 15.5 \pm 0.50 ^a | 13.5 \pm 4.37 ^a | 31.7 \pm 1.33 ^a |
| CV (%) | 8.42 | 26.43 | 20.93 | 16.70 | 25.71 | 8.31 | 29.30 | 10.47 | 22.07 | 15.88 | 68.74 | 48.47 |
| P | 0.316 | 0.314 | 0.459 | 0.013 | 0.003 | 0.065 | 0.003 | 0.493 | 0.001 | 0.013 | 0.013 | 0.026 |

N: number of repetitions; PP: polypropylene bag; PP_AP: polypropylene bag with aluminum phosphide tablet; PP_SL: polypropylene bag with standard lime (calcium hydroxide); PP_ML: polypropylene bag with micronized lime (calcium hydroxide); SPB: silage plastic bag; PBO: plastic Bottle; HBT: GrainPro hermetic SuperGrainbag® Farm; HBZ: GrainPro hermetic SuperGrainbag® Premium RZ with zip; HMS: hermetic metal silo. P: p-value of the overall mean; different letters within the same column indicate statistically significant differences from the initial sample obtained with the Dunnett's test ($p < 0.05$); CV: coefficient of variation of samples from the same experiment; na: not available; ns: no sufficient grain without apparent damage; grey area indicates that the technology was not tested at the corresponding site and year.

Table 6
Effect of storage technologies on total color difference between the initial samples and final samples, after six months of storage at different experimental sites (mean ± standard error).

| Parameters (elevation) | Texcoco (2282 masl) | | Yanhuitlán (2138 masl) | | Zacualtipán (2070 masl) | | Pochutla (202 masl) | | Cotzocón (113 masl) | | Peto (36 masl) | |
|-----------------------------------|-----------------------|-----------------------|------------------------|-----------------------|-------------------------|-----------------------|---------------------|------|------------------------|------------------------|-----------------------|-----------------------|
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Total color difference (ΔE*): N=3 | | | | | | | | | | | | |
| PP | 0.9±0.19 ^a | 2.5±0.58 ^a | na | | 3.8±0.50 ^a | | | | | | 3.5±0.63 ^a | ns |
| PP_AP | | | na | 3.5±1.22 ^a | | | na | | 7.2±0.63 ^a | 6.7±1.06 ^a | | |
| PP_SL | | | | | | | na | ns | | | | |
| PP_ML | 6.9±0.81 ^b | | | | | | | | 8.0±0.59 ^{ab} | | 9.1±0.92 ^b | 9.9±1.33 ^a |
| SPB | | | | | | | | | | 6.2±0.38 ^a | | |
| PBO | | 2.6±0.57 ^a | | | | | | na | | | | 3.0±0.35 ^b |
| HBT | | | na | 2.2±0.89 ^a | 1.6±0.34 ^a | | na | na | 5.7±0.68 ^a | 6.6±0.75 ^a | | 3.3±0.15 ^b |
| HBZ | 1.5±0.39 ^a | 3.1±0.57 ^a | | | | 3.8±0.74 ^a | | | | | 2.9±0.66 ^a | |
| HMS | 2.3±0.35 ^a | 1.4±0.63 ^a | na | 3.5±0.59 ^a | 2.4±0.26 ^a | 2.8±0.57 ^a | na | na | 4.8±1.47 ^{bc} | 8.1±0.72 ^{bc} | 3.1±1.36 ^a | 4.8±0.52 ^b |
| CV (%) | 87.73 | 44.51 | na | 50.75 | 30.40 | 29.90 | na | na | 29.37 | 22.72 | 65.01 | 58.94 |
| P | <0.001 | 0.318 | - | 0.543 | 0.170 | 0.480 | | | 0.130 | 0.112 | 0.005 | 0.001 |

N: number of repetitions; PP: polypropylene bag; PP_AP: polypropylene bag with aluminum phosphide tablet; PP_SL: polypropylene bag with standard lime (calcium hydroxide); PP_ML: polypropylene bag with micronized lime (calcium hydroxide); SPB: silage plastic bag; PBO: plastic Bottle; HBT: GrainPro hermetic SuperGrainbag® Farm; HBZ: GrainPro hermetic SuperGrainbag® Premium RZ with zip; HMS: hermetic metal silo. P: p-value of the overall mean; different letters within the same column indicate statistically significant differences from the initial sample obtained with the Dunnett's test (p < 0.05); CV: coefficient of variation of samples from the same experiment; na: not available; ns: no sufficient grain without apparent damage; grey area indicates that the technology was not tested at the corresponding site and year.

conditions inside non-hermetic containers (interactions with the environment, oxygen availability, temperature and relative humidity). Harrington (1972) stated that grain moisture content and its relationship with relative humidity and ambient temperature are important factors for seed longevity. Seed stored in non-hermetic containers are exposed to variations in ambient relative humidity whereas relative humidity remains relatively constant under hermetic storage (Baoua et al., 2018). Even though the average moisture content of the seed before storage was below 13%, an increase in the equilibrium moisture content is probable with non-hermetic technologies, which may reduce seed viability (Bradford et al., 2018). Ambient temperature is also important, as seed viability diminishes in warm environments (Harrington, 1972). Another factor in the conservation of dry seed is oxygen availability, which can cause oxidative reactions, rancidity and loss of germination capacity (Bewley et al., 2013; Paraginski et al., 2014). Hermetic technologies preserve seed quality by reducing contact with the environment, maintaining a low equilibrium relative humidity, seed dryness, and limiting the availability of oxygen during storage (Afzal et al., 2017; Bradford et al., 2018; Tubbs et al., 2016).

Regarding grain macronutrients composition, there was little variation or effect of storage technology on starch, protein, oil, or ether extract contents of grains before and after storage even for grain stored

using non-hermetic technologies. Stathers et al. (2020) recently found no significant change during storage in macronutrient contents of uninfested grain, while carbohydrate, protein, and fat content losses were reported for grain infested with *S. zeamais* and *P. truncatus*. The current study analyzed grain samples without apparent damage, in line with farmers' preferences in grain or seed, which could explain why fewer differences in macronutrient composition were found. However, the large percentages of insect-damaged grain (up to almost 60% in lowland conditions) and fungi-damaged grain (up to almost 15%) reported by Odjo et al. (2020) for conventional storage technologies, could result in quality losses that are larger than those found in the samples without apparent damage.

Even though no significant effect of storage technologies on macronutrients contents was recorded, significant differences were observed for total ferulic acids and acid p-coumaric contents, although without a clear trend. Previous studies have reported maize grain phenolic content as negatively correlated with weight loss (Arnason et al., 1993). A reduction of phenolic compounds after storage has been demonstrated for black rice (Lang et al., 2019; Norkaew et al., 2017) and sorghum (de Oliveira et al., 2017) and was associated with oxidative degradation, suggesting a possible reduction of phenolic contents during storage using hermetic technologies would be less significant. Recently Nkhata

Table 7
Partial correlation between grain quality parameters, grain characteristics and postharvest loss parameters (Degree of freedom = 78; significant correlation -P<0.05- in bold).

| Parameters | | Quality parameters | | | | | | | | | |
|-----------------------------|------------------------|--------------------|------------------|------------------|------------------|--------------------|------------------|-----------------------|------------------|------------------------------|------------------|
| | | Normal seedlings | Germination | Fat acidity | P-coumaric acid | Total Ferulic acid | Ether extract | Hundred kernel weight | Flotation index | Total color difference (ΔE*) | |
| Grain characteristics | Grain moisture content | r | -0.517 | -0.372 | 0.553 | 0.197 | -0.250 | 0.183 | 0.301 | 0.535 | 0.135 |
| | | P | <0.001 | 0.001 | <0.001 | 0.079 | 0.025 | 0.105 | <0.001 | <0.001 | 0.232 |
| | Grain temperature | r | 0.227 | 0.132 | -0.254 | -0.211 | 0.381 | 0.002 | -0.661 | -0.614 | 0.100 |
| | | P | 0.043 | 0.244 | 0.023 | 0.610 | <0.001 | 0.986 | <0.001 | <0.001 | 0.377 |
| Postharvest loss parameters | Insect damage | r | -0.625 | -0.657 | 0.532 | 0.356 | 0.013 | 0.099 | -0.250 | 0.426 | 0.416 |
| | | P | <0.001 | <0.001 | <0.001 | 0.001 | 0.906 | 0.384 | 0.003 | <0.001 | <0.001 |
| | Fungi damage | r | -0.472 | -0.525 | 0.278 | 0.297 | 0.026 | -0.009 | 0.408 | 0.483 | 0.161 |
| | | P | <0.001 | <0.001 | 0.013 | 0.007 | 0.821 | 0.936 | <0.001 | <0.001 | 0.153 |
| | Weight loss | r | -0.566 | -0.544 | 0.618 | -0.024 | -0.109 | -0.158 | -0.362 | 0.356 | 0.456 |
| | | P | <0.001 | <0.001 | <0.001 | 0.831 | 0.336 | 0.162 | <0.001 | 0.001 | <0.001 |
| | Total damage | r | -0.728 | -0.743 | 0.616 | 0.435 | -0.100 | 0.074 | -0.006 | 0.692 | 0.397 |
| | | P | <0.001 | <0.001 | <0.001 | <0.001 | 0.375 | 0.515 | 0.942 | <0.001 | <0.001 |
| | Live maize weevil | r | -0.651 | -0.673 | 0.586 | 0.334 | 0.015 | 0.019 | -0.318 | 0.337 | 0.451 |
| | | P | <0.001 | <0.001 | <0.001 | 0.002 | 0.892 | 0.431 | <0.001 | 0.002 | <0.001 |
| Live large grain borer | r | -0.613 | -0.655 | 0.689 | 0.023 | -0.007 | -0.063 | -0.206 | -0.694 | 0.491 | |
| | P | <0.001 | <0.001 | <0.001 | 0.840 | 0.953 | 0.576 | 0.016 | <0.001 | <0.001 | |

et al. (2021) reported an increase in phenolic contents during storage of biofortified grain in woven bags in comparison with hermetic PICS bags, suggesting an enzymatic release of bound phenolics previously esterified to cell wall components (Ziegler et al., 2018). Phenolic content in maize grain has been found to affect pasting properties, porridge quality and the end-use quality of nixtamalized dough for making tortillas (Del Pozo-Insfran et al., 2006; Herrera-Sotero et al., 2017; Salinas-Moreno et al., 2017). Therefore, further investigation on the effect of storage technologies on maize polyphenol and anthocyanin contents is required, particularly for products such as blue, red and pink maize that have higher polyphenol contents with associated health benefits and recently increased market interest (Blare et al., 2020; Nkhata et al., 2021).

Fat acidity increased during storage, particularly in grain stored using non-hermetic technologies and at sites below 500 masl, which suggests hydrolysis of triglycerides. This has been demonstrated elsewhere for maize (Hernández et al., 2009; Mestres et al., 2003, 2009; Paraginski et al., 2014) and for rice (Genkawa et al., 2008; Park et al., 2012) and is associated with postharvest management as well as storage time, storage temperature and fungal infection—the latter possibly providing enzymes that degrade fat and release fatty acids. Fat acidity is generally an indicator of poor storage and has been proposed as a quality parameter for grain commercialization norms in Mexico. This parameter is linked with fungi contamination, which may provide enzymes for fat degradation and the release of free fatty acids. A positive and significant correlation between fat acidity and postharvest loss parameters was shown in this study, suggesting that poor storage conditions were also associated with grain quality losses even in samples not showing fungal infections.

The physical properties of grain are important for processing and they influence varietal preferences. While this study showed no clear effect of storage technologies on hundred kernel weight, an increase in flotation index after six months of storage was found, especially for grain stored using non-hermetic technologies. Flotation index is an indirect measure of grain hardness, used in Mexico to estimate the time required for nixtamalization. Grain with a high flotation index is less suited for conventional nixtamalization, with low yields of cooked grain (Billeb de Sinibaldi and Bressani, 2001; NMX-FF-034/1-SCFI-2002 Norma Mexicana, 2002; Rooney and Suhendro, 2001). Samples collected from Peto in 2017 and 2018 showed respective 700% and 200% increases in flotation index, after storage in polypropylene bags with micronized lime, suggesting that the use of non-hermetic technologies can lead to a loss of density in grain endosperm during storage, through exposure to moisture or insect damage. High moisture content has been found to decrease the bulk density and increase the porosity of stored wheat, barley and legume grain (Al-Mahasneh and Rababah, 2007; Altuntas and Demirtola, 2007; Sologubik et al., 2013). Korunic et al. (1998) also reported a decrease in grain bulk density and flow properties due to the addition of diatomaceous earth to grain during storage and a commensurate increase in friction between stored kernels. After six months of storage in non-hermetic conditions, particularly in tropical areas, grain moisture content increased (Odjo et al., 2020), which, together with air uptake during storage, may explain the increase in the flotation index. Internal insect feeding and particularly high levels of insect damage in stored grain were also associated with high flotation index.

Total color difference was also affected by storage technology, with significant changes recorded only for grain stored with inert dusts. These higher values of total color difference seem to be related to a decrease in a^* and b^* values (supplementary table A4). Changes in grain color during storage, which may lower the grain's value on markets, is associated with storage conditions (moisture content, temperature, and duration) (Mohammadi Shad and Atungulu, 2019; Shafiekhani et al., 2018) and polyphenol oxidase activity (Quinde et al., 2004; Salinas-Moreno et al., 2006). The fact that the only significant differences resulted from the use of lime and micronized lime as conditioning agents suggests that the discoloration reported may be associated with moisture uptake during storage in non-hermetic technologies, which may in turn

facilitate biochemical reactions such as oxidation. However, discoloration of grain during storage is a complex process that involves many different mechanisms, especially for yellow and orange maize varieties, where carotenoids can degrade during storage with implication in both end-use and nutritional quality (Taleon et al., 2017).

The correlation analyses highlighted a positive association between postharvest loss and flotation index and fat acidity of stored samples, and a negative association between postharvest loss and seed germination parameters. Grain and seed quality losses (seed germination, mycotoxin contamination, discoloration) of kernels infested by fungi and insects under storage with similar non-hermetic technologies have been documented in Kenya (Njoroge et al., 2014; Walker et al., 2018). The present study demonstrated that poor storage conditions are also detrimental for grain that may not be infested or infected or show apparent damage. Even though most macronutrients contents in uninfested grain remain stable during storage, moisture content and oxygen availability may promote biochemical reactions that reduce grain and seed quality. These reactions seem to be more important at sites below 500 masl, due to higher temperatures and relative humidity. Regardless of environmental/geographical conditions, hermetic storage limits such reactions and minimizes grain and seed quality losses during storage by cutting-off gas exchanges and maintaining the original grain moisture content. Non-hermetic technologies, including polypropylene bags with or without conditioning agents such as inert dusts, failed to achieve that. The conditioning agents may help protect against insects (Odjo et al., 2020), but tend to favor moisture uptake and quality loss. Generally, smallholders in Latin America discard visually damaged grain or use it to feed animals but, in cases of food insecurity, they may also mix damaged kernels with healthy maize for human consumption (Mendoza et al., 2017). In all cases, postharvest loss reduces smallholders' food security by decreasing the amount of food available and have nutritional and health consequences due to quality losses and increased exposure to mycotoxins. Given smallholders' relatively low awareness regarding these issues, it is critical to promote good grain handling and storage practices throughout the postharvest value chain in Mexico and to facilitate farmers' access to technologies that minimize losses of quantity and quality (Stathers et al., 2020).

In conclusion, the current study showed that environmental conditions and storage technologies associated with postharvest loss can also reduce the quality of apparently undamaged kernels stored in the same conditions, increasing fat acidity and flotation index and reducing grain density and seed germination capacity. Farmers' conventional, non-hermetic storage technologies, including polypropylene bags with or without conditioning agents, resulted in a loss of as much as 95% of seed germination after six months of storage, particularly below 500 masl, as well as reduced grain quality based on parameters such as flotation index and fat acidity. In contrast, hermetic technologies, including recycled containers such as plastic bottles, maintained seed quality and minimized grain quality losses, regardless of storage conditions. This study provided additional evidence of the effectiveness of hermetic storage technologies in minimizing quantitative and qualitative losses in smallholder farming systems in Mexico. Additional studies may focus on how to promote these technologies in rural areas while identifying key aspects of the success of postharvest interventions.

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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.

Data availability statement

The data are freely available at DataVerse: Verhulst, Nele; Odjo, Sylvanus; Palacios, Natalia, 2021, "Data for: Hermetic storage technologies preserve maize seed quality and minimize grain quality loss in smallholder farming systems in Mexico", <https://hdl.handle.net/11529/10548569>, CIMMYT Research Data & Software Repository Network, V1, UNF:6:tMRAHkVtYu+mUOU5kzFcyw== [fileUNF]

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jaspr.2022.101954>.

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