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Research Article

Maize Grain Stored in Hermetic Bags: Effect of Moisture and Pest Infestation on Grain Quality

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Maize (*Zea mays*) is an important staple food crop produced by the majority of smallholder farmers that provides household food security through direct consumption and income generation. However, postharvest grain losses caused by insect pests during storage pose a major constraint to household food security. Hermetic storage technology is an alternative method that minimises postharvest losses by depleting oxygen and increasing carbon dioxide levels within the storage container through metabolic respiration of the grains, insects, and microorganism. Maize grain was stored for 180 days in hermetic bags or open-weave polypropylene bags to compare quality preservation when subject to initial grain moisture contents of 12, 14, 16, and 18 percent and infestation by *Sitophilus zeamais*. The moisture content of grain in hermetic bags remained unchanged while in polypropylene bags decreased. Dry grains (12% moisture content) stored well in hermetic bags and suffered 1.2% weight loss while for equivalent grains in polypropylene bags the weight loss was 35.8%. Moist grains (18% moisture content) recorded the lowest insect density (7 adults/kg grain) in hermetic bags while polypropylene bags had the highest (1273 adults/kg grain). Hermetic and polypropylene bags recorded the lowest (0–4 adults/kg grain) and highest (16–41 adults/kg grain) *Prostephanus truncatus* population, respectively. Discoloured grains were 4, 6, and 12 times more in grains at 14, 16, and 18 than 12 percent moisture content in hermetic bags. Grains at 18% moisture content recorded significantly lower oxygen (10.2%) and higher carbon dioxide (18.9%) levels. Holes made by *P. truncatus* in the hermetic bags were observed. In conclusion, storage of moist grains (14–18% moisture content) in hermetic bags may pose health risk due to grain discolouration caused by fungal growth that produces mycotoxins if the grains enter the food chain. The study was on only one site which was hot and dry and further investigation under cool, hot, and humid conditions is required.

1. Introduction

Maize (*Zea mays* L.) is an important staple food in sub-Saharan Africa but is also used for industrial purposes and animal feed worldwide [1]. In the tropics, in locations where there are two annual maize harvests, it is not uncommon for one harvest to coincide with the start of the rainy season. As nearly all smallholder farmers rely on sun-drying prior to grain storage, this poses a serious threat of grain quality deterioration [2]. If the crop is stored while still moist and warm, there may be rapid spoilage due to mould growth and insect pests [3]. Due to the demand for high quality and safe food by the consumers, there is a need to maintain and protect maize grain from insect damage and fungal infection [4].

Important physical factors that may affect the quality of stored grain are moisture content; temperature; the type of storage structure used; and the gaseous environment, particularly levels of carbon dioxide and oxygen [5]. All these factors may have interactive effects on mould growth and insect pests [6, 7], evolution of carbon dioxide [8], and grain colour and weight [9]. The optimum temperature for the development of storage moulds and insects is generally around 30°C. Requirements for moisture are more wide ranging, with most moulds failing to germinate below 80% relative humidity but insect needing a grain moisture content of at least 10% to 12% [10], which is typically in equilibrium with around 50% to 70% relative humidity. When grain with higher moistures (>14%) is stored under warm conditions, mould growth may result in serious quality changes [3], and insect attack may reduce quality and cause weight losses. Simple and low cost storage facilities that isolate grains from unfavourable environmental conditions are therefore required by farmers.

The main insect pests of stored maize include the larger grain borer *Prostephanus truncatus* (horn) (Coleoptera: Bostrichidae) and maize weevil *Sitophilus zeamais* (Motschulsky) (Coleoptera: Curculionidae) [11]. For the past 35 years, sub-Saharan Africa has witnessed the outbreak and spread of larger grain borer (LGB) in 20 countries [12]. The impact of insect infestation of stored grain is usually expressed as percentage weight loss [13]. Losses as high as 36% have been documented on stored maize in Benin [14] and 35% in Kenya [15]. The losses are attributed to the use of ineffective storage structures such as cribs, jute, and polypropylene bags for storing grains [16]. These losses affect the food security and income of the 90% of the Kenyan population that relies on the crop as staple food [17] besides contributing to increased food prices due to removal of part of the supply from the market [18].

A promising technology to store grains safely is airtight (hermetic) storage (self-regulated modified atmosphere). The technology was developed in response to concern about the adverse effects of pesticide residues in grains and environment [19]. The respiration of the grains, insects, and moulds within hermetic stores result in depletion of oxygen and increase of carbon dioxide [20, 21]. Under such conditions, fungal growth may be inhibited [22], and when the oxygen level falls to 10%, insect activity is reduced and insect will die if subjected to less than 2% oxygen for periods in excess of 14 days. Consequently, hermetic storage can be used to maintain grain quality without the need for pesticide application [23]. The rate at which oxygen is reduced and carbon dioxide generated is a function of both grain moisture content and the ambient temperature; the rate is low at temperatures below 20°C [24].

Storage systems based on the hermetic principle include airtight bags, bunkers, and silos. While hermetic metal silos [25] and polythene (plastic) bags [26] have been developed, their use for storage of grains by smallholder farmers is still limited. There is also scant information on the storability of maize grain at the range of moisture contents that are typical in tropical storage systems. The key to successful hermetic storage is air-tightness and control of moisture content. The present study was undertaken to investigate quality change of maize stored in hermetic bags subject to infestation by *Sitophilus zeamais* and a variety of initial grain moisture content level. The parameters monitored were moisture content, grain discolouration, insect density, weight loss, and oxygen and carbon dioxide levels.

2. Materials and Methods

2.1. Preparation of Maize Grain. Hybrid maize (H614) was cleaned to remove mouldy and broken grains and foreign materials and sun-dried to 12% moisture content. Samples of grain at three further moisture contents 14, 16, and 18% were prepared by adding predetermined amount of distilled water then mixing thoroughly in plastic bags [3, 27]. The amount of water added was calculated as follows: $Q = A((b-a)/(100-a))$, where A = weight of grain, b = desired moisture content, and a = initial grain moisture content. The bags were then kept in a cold room for two weeks. Every other day, the bags were retrieved, grains mixed, and returned to the cold room. Prior to the conditioning of the grains, four grain samples were taken and tested for moisture content using a Foss Infratec™ 1241 grain analyzer (Sweden) and weight as the baseline. The moisture content of the maize grain in the 12, 14, 16, and 18% categories was close to the desired ones: 12.4 ± 0.0, 14.3 ± 0.1, 16.2 ± 0.2, and 18.2 ± 0.2% (wet basis), respectively, while the quality of the grains was 1.2 ± 0.2% discoloured at the start of the storage period.

2.2. Test Storage Bags. The storage bags tested were SuperGrain IV-R™ bag (74 cm wide and 64 cm length) of 25 kg holding capacity (supplied by GrainPro Inc.) and open-weave polypropylene bags of the same capacity. The SuperGrain IV-R™ bag is tougher than the earlier version of the SuperGrain bag and has an extremely low oxygen permeability (<4 cc/m^2/day) in which oxygen is reduced from 20% to 8% in 14 days for *P. truncatus* under controlled conditions of 27 ± 1°C and 75 ± 1% relative humidity [28]. As recommended by the manufacturer, each SuperGrain IV-R™ bag was placed inside a woven polypropylene bag to provide support and handling convenience. The open ends of SuperGrain IV-R™ bags were cut to fit the height dimension of these polypropylene outer bags.

2.3. Experimental Procedure. The bags were each filled with 20 kg maize grains and then "seeded" with 20 live adult maize weevil (1 beetle/kg grain). The barn had an LGB population and were interested to see whether this pest would penetrate from the outside into the bags (entry holes) while *S. zeamais* on the inside potentially made emergence holes on the grains. The bags were closed according to manufacturer's instructions: the entrapped air was squeezed out and then secured tightly with rubber straps. The grains were not inoculated with fungi since maize usually harbours sufficient fungal spores that fungal growth will occur naturally if environmental conditions are conducive. The experiment consisted of eight treatments with four replications: (1) SuperGrain IV-R™ bag + grains at 12% moisture content; (2) SuperGrain IV-R™ bag + grains at 14% moisture content; (3) SuperGrain IV-R™ bag + grains at 16% moisture content; (4) SuperGrain IV-R™ bag + grains at 18% moisture content; (5) Polypropylene bag + grains at 12% moisture content; (6) Polypropylene bag + grains at 14% moisture content; (7) Polypropylene bag + grains at 16% moisture content; and (8) Polypropylene bag + grains at 18%

moisture content. To monitor hermetic conditions, carbon dioxide levels were measured using a MOCON® portable oxygen/carbon dioxide analyzer (Pac Check® 325, Mocon Inc, USA). Measurement of carbon dioxide in polypropylene bags was not considered worthwhile as their open weave would allow free exchange of gas and so it was not expected to accumulate carbon dioxide. These measurements were taken every seven days and their means at the end of each storage period calculated.

The bags were stored in a completely randomised factorial design in an open side barn at ambient conditions. The ambient mean monthly temperatures and relative humidity in the barn during the trial were 26°C (range 23–30°C) and 54% (range 46–58%), respectively. The highest and lowest mean temperatures were recorded in March/April and June/July, respectively. For relative humidity, the highest records were in April and lowest records in September. Grain bags were sampled destructively after 60, 120, and 180 days storage.

At each sampling interval, bags were unsealed, and about 350 g grains were drawn using a 6-slot probe from the centre and four cardinal points. The samples were put in labelled plastic bags and taken to the laboratory for grain damage analysis. A set of 4.75 mm and 1.0 mm aperture size sieves (Endecott Ltd, UK) were used to separate grains and flour from the insects. Record of adult insects was taken according to species. After sieving, the grains were tested for moisture content using the Foss Infratec™ 1241 grain analyzer. Half of the grain samples obtained using riffle divider were analysed for damage. The grains were sorted into undamaged, damaged, and discoloured fractions. The number of grains and the weight of each fraction were recorded. The grains were weighed on a precision electronic scale (to two decimal points). Discoloured grains were expressed as a percentage of the total number of grains. A grain was regarded discoloured when its surface was darkened. Grain weight loss was determined by count and weight method [29]:

$$\text{discoloured grain}\,(\%) = \frac{\text{number of discoloured grain}}{\text{total number of grain}} \times 100,$$

$$\text{weight loss}\,(\%) = \frac{[(W_u \times N_d) - (W_d \times N_u)]}{W_u \times (N_u + N_d)} \times 100, \tag{1}$$

where W_u = weight of undamaged grain; N_u = number of undamaged grain; W_d = weight of damaged grain; and N_d = number of damaged grain.

The full contents of each bag were also sieved and all insects present counted according to the species. The insect counts were added to those obtained from the 350 g samples to give a total number of insects present. The total number of adult insects per bag were divided by the initial grain weight (20 kg) and recorded as number of insects per kilogram.

3. Statistical Analysis

The number of insects was transformed to $\log_{10}$ (count + 1), while percent discoloured grain, weight loss, and oxygen and carbon dioxide data were square root ($\sqrt{x}$) transformed in order to stabilize the variances. The transformed data were first analysed using one-way repeated measures ANOVA (SPSS version 20, IBM Corporation 2011) to compare grain moisture content, insect numbers, percent discoloured grain weight loss, and oxygen and carbon dioxide at each storage time among the treatment as the response variable and treatment as the main effect. Storage time represented the repeated factor. Afterwards and separately, each response variable was analyzed using general linear model procedure of GenStat Release 12.1 (VSN International Ltd 2009), with treatment as main effect. Significant differences between the means were separated by the Student–Newman–Keuls (SNK) test at $P < 0.05$. However, for ease of understanding, the untransformed means are presented.

4. Results

4.1. Grain Moisture Content and Grain Discolouration. The grain moisture content differed significantly with treatments ($F_{7,24}$ = 2643.48; $P < 0.0001$; coefficient of variation = 0.99) and storage period ($F_{2,48}$ = 1611.92; $P < 0.0001$; coefficient of variation = 0.87). Significant interaction ($P < 0.0001$; coefficient of variation = 0.88) was also detected. The treatment effects explained the significant differences observed. SuperGrain IV-R™ bag maintained moisture content of the grains constantly throughout the storage period (Table 1). The equivalent grains stored in polypropylene bags showed a decrease in grain moisture content over the same storage period, with the final contents ranging from 11.2 to 11.6% after 180 days storage (Table 1). The presence of fermented smell in moist grains at 18% initial moisture content stored in the hermetic bag was observed.

There were differences in the percentage grain discolouration with treatments ($F_{7,24}$ = 191.23; $P < 0.0001$; coefficient of variation = 0.98) and storage period ($F_{2,48}$ = 88.56; $P < 0.0001$; coefficient of variation = 0.79). The interaction ($P < 0.0001$; coefficient of variation = 0.88) was also significant. The significant differences observed in grain discolouration were explained by the treatment effects. The discoloured grains were 4, 6, and 12 times more in the grains stored in hermetic bags at 14, 16, and 18 than grains with 12% initial moisture content at the end of the experiment, respectively (Table 2). For the grains stored in polypropylene bags, the percentage discolouration reduced with storage period. The grain darkening and its associated off-odour were indicative of spoilage and changes in the quality of the grains.

4.2. Infestation by Sitophilus zeamais and Prostephanus truncatus. Although the grain was deliberately seeded with *S. zeamais*, infestation by *P. truncatus* occurred naturally from a residual population in the barn, thus both insect species were followed during the study. The number of adult *S. zeamais* differed significantly with treatment ($F_{7,24}$ = 197.46; $P < 0.0001$; coefficient of variation = 0.98) and storage period ($F_{2,48}$ = 83.15; $P < 0.0001$; coefficient of variation = 0.78). The interaction was significant ($P < 0.002$;

Table 1: Mean (±SE) percent grain moisture content after 60, 120, and 180 days of storage.

Treatment	Storage period (days)		
	60	120	180
Polypropylene bag + 12% MC grain	12.1 ± 0.1a	11.7 ± 0.1a	11.2 ± 0.0a
Polypropylene bag + 14% MC grain	13.4 ± 0.1b	12.4 ± 0.1c	11.6 ± 0.0b
Polypropylene bag + 16% MC grain	13.6 ± 0.1b	12.4 ± 0.1c	11.6 ± 0.2b
Polypropylene bag + 18% MC grain	13.9 ± 0.1c	12.6 ± 0.1c	11.5 ± 0.0b
SuperGrain IV-R™ bag + 12% MC grain	12.0 ± 0.1a	12.0 ± 0.1b	12.0 ± 0.1c
SuperGrain IV-R™ bag + 14% MC grain	14.2 ± 0.0c	14.1 ± 0.1d	14.1 ± 0.0d
SuperGrain IV-R™ bag + 16% MC grain	16.0 ± 0.1d	15.9 ± 0.1e	16.0 ± 0.1e
SuperGrain IV-R™ bag + 18% MC grain	18.0 ± 0.1e	18.1 ± 0.1f	17.9 ± 0.1f
F value	495.90	603.06	561.20
P value	<0.001	<0.001	<0.001

Means within a column followed by the same letter are not significantly different (SNK test, $P > 0.05$).

Table 2: Mean (±SE) percent grain discolouration after 60, 120, and 180 days of storage.

Treatment	Storage period (days)		
	60	120	180
Polypropylene bag + 12% MC grain	2.7 ± 0.2b	2.4 ± 0.2ab	0.2 ± 0.2a
Polypropylene bag + 14% MC grain	5.5 ± 0.2c	4.1 ± 0.8b	0.0 ± 0.0a
Polypropylene bag + 16% MC grain	4.5 ± 0.2c	2.5 ± 0.2ab	0.1 ± 0.1a
Polypropylene bag + 18% MC grain	7.6 ± 0.7d	6.2 ± 0.5c	0.8 ± 0.2b
SuperGrain IV-R™ bag + 12% MC grain	1.6 ± 0.1a	1.9 ± 0.1a	2.3 ± 0.8c
SuperGrain IV-R™ bag + 14% MC grain	9.5 ± 0.4e	10.0 ± 0.9d	9.2 ± 0.6d
SuperGrain IV-R™ bag + 16% MC grain	14.1 ± 0.9f	10.0 ± 0.9d	13.0 ± 0.6e
SuperGrain IV-R™ bag + 18% MC grain	20.3 ± 1.0g	19.2 ± 2.5e	28.2 ± 1.9f
F value	99.97	45.13	175.95
P value	<0.001	<0.001	<0.001

Means within a column followed by the same letter are not significantly different (SNK test, $P > 0.05$).

coefficient of variation = 0.65). The significant differences observed were explained by the treatment effects. The population increased marginally 180 days after storage (7–60 adults/kg grain) in SuperGrain IV-R™ bags compared to equivalent grains (894–1273 adults/kg grain) stored in polypropylene bags (Table 3). SuperGrain IV-R™ bag with moist grains (18% moisture content) recorded the lowest insect density (7 adults/kg grain) while equivalent grains in polypropylene bags had the highest insects (1273 adults/kg grain) (Table 3). Very few *S. zeamais* survived in moist grains stored in SuperGrain IV-R™ bags, and the population was almost the same throughout the storage duration.

The mean difference of the number of adult *P. truncatus* differed significantly with treatment ($F_{7,24} = 65.26$; $P < 0.0001$; coefficient of variation = 0.95) and storage period ($F_{2,48} = 55.78$; $P < 0.0001$; coefficient of variation = 0.70). The interaction was also significant ($P = 0.002$; coefficient of variation = 0.48). The significant differences observed were explained by the treatment effects. Grains stored in SuperGrain IV-R™ bags were infested with *P. truncatus* 120 days after storage. The population increased marginally 180 days after storage (ranged from 0–10 adults/kg grain) compared to equivalent grains stored in polypropylene bags (Table 4). Overall, SuperGrain IV-R™ bags and polypropylene bags had the lowest (0–4 adults/kg grain) and highest (16–41 adults/kg grain) insects (Table 4).

4.3. Grain Weight Loss. At the onset of the storage, the weight loss of the grains was 1.2 ± 0.2%. There were significant mean differences in percentage weight loss with treatment ($F_{7,24} = 4804.14$; $P < 0.0001$; coefficient of variation=0.99) and storage period ($F_{2,48} = 5521.98$; $P < 0.0001$; coefficient of variation = 0.99). The interaction was also significant ($P < 0.0001$; coefficient of variation = 0.99). The significant differences observed were explained by the interaction effects. The results showed significantly increasing trend in grain weight loss over the storage period and treatment. The mean percentage weight loss increased from 1.9 to 20.9 (Table 5) after 180 days of storage. Grain at 12% moisture content stored in the SuperGrain IV-R™ bags recorded the lowest (1.2%) while grains at 16% moisture content stored in polypropylene bags incurred highest (42.6%) weight loss (Table 5). Overall, irrespective of initial grain moisture content, SuperGrain IV-R™ bags prevented and maintained almost similar grain weight loss (≤1%) compared to equivalent grains in polypropylene bags over 120 days after storage. As grains in the polypropylene bags lost moisture during the storage period, significantly higher losses were observed (Table 5). By the end of storage period, grains at 12% initial moisture content stored in SuperGrain IV-R™ bags suffered least weight loss (1.2%), translating to 96.6% weight loss reduction, compared to the equivalent grains in polypropylene bags.

Table 3: Mean (±SE) number of adult *Sitophilus zeamais* per kilogram of grain after 60, 120, and 180 days of storage.

Treatment	Storage period (days)		
	60	120	180
SuperGrain IV-R™ bag + 12% MC grain	4 ± 1a	33 ± 8b	60 ± 9b
SuperGrain IV-R™ bag + 14% MC grain	8 ± 4a	9 ± 4a	8 ± 1a
SuperGrain IV-R™ bag + 16% MC grain	6 ± 1a	11 ± 3a	8 ± 2a
SuperGrain IV-R™ bag + 18% MC grain	2 ± 1a	9 ± 5a	7 ± 1a
Polypropylene bag + 12% MC grain	163 ± 123b	685 ± 55c	961 ± 20c
Polypropylene bag + 14% MC grain	331 ± 37c	1092 ± 18c	1043 ± 99c
Polypropylene bag + 16% MC grain	439 ± 113c	1230 ± 134c	894 ± 94c
Polypropylene bag + 18% MC grain	54 ± 15b	1227 ± 165c	1273 ± 57c
F value	28.79	78.97	408.42
P value	<0.001	<0.001	<0.001

Means within a column followed by the same letter are not significantly different (SNK test, $P > 0.05$).

Table 4: Mean (±SE) number of adult *Prostephanus truncatus* per kilogram of grain after 60, 120, and 180 days of storage.

Treatment	Storage period (days)		
	60	120	180
SuperGrain IV-R™ bag + 12% MC grain	0 ± 0a	1 ± 1a	4 ± 2b
SuperGrain IV-R™ bag + 14% MC grain	0 ± 0a	0 ± 0a	10 ± 9b
SuperGrain IV-R™ bag + 16% MC grain	0 ± 0a	1 ± 0a	3 ± 2b
SuperGrain IV-R™ bag + 18% MC grain	0 ± 0a	1 ± 1a	0 ± 0a
Polypropylene bag + 12% MC grain	8 ± 1b	74 ± 6c	41 ± 3c
Polypropylene bag + 14% MC grain	6 ± 2b	18 ± 3b	41 ± 5c
Polypropylene bag + 16% MC grain	10 ± 6b	17 ± 5b	40 ± 5c
Polypropylene bag + 18% MC grain	3 ± 1b	16 ± 3b	30 ± 3c
F value	16.09	61.90	20.84
P value	<0.001	<0.001	<0.001

Means within a column followed by the same letter are not significantly different (SNK test, $P > 0.05$).

Table 5: Mean (±SE) percentage weight loss after 60, 120, and 180 days of storage.

Treatment	Storage period (days)		
	60	120	180
Polypropylene bag + 12% MC grain	1.6 ± 0.1d	15.2 ± 0.5d	35.8 ± 0.1d
Polypropylene bag + 14% MC grain	4.3 ± 0.5e	19.7 ± 0.3e	40.7 ± 0.3c
Polypropylene bag + 16% MC grain	5.6 ± 0.1f	21.8 ± 0.2f	42.6 ± 0.7f
Polypropylene bag + 18% MC grain	1.3 ± 0.1cd	20.9 ± 0.6f	40.1 ± 0.1e
SuperGrain IV-R™ bag + 12% MC grain	0.2 ± 0.0a	0.3 ± 0.1a	1.2 ± 0.1a
SuperGrain IV-R™ bag + 14% MC grain	1.0 ± 0.0bc	0.9 ± 0.1c	3.0 ± 0.2c
SuperGrain IV-R™ bag + 16% MC grain	0.8 ± 0.0b	0.8 ± 0.0c	2.0 ± 0.1b
SuperGrain IV-R™ bag + 18% MC grain	0.4 ± 0.1a	0.5 ± 0.1b	1.8 ± 0.1b
F value	143.60	1947.75	5307.88
P value	<0.001	<0.001	<0.001

Means within a column followed by the same letter are not significantly different (SNK test, $P > 0.05$).

4.4. Carbon Dioxide Levels. The carbon dioxide levels recorded in the grains at different initial grain moisture contents stored in the SuperGrain IV-R™ bag affected the insect population observed in the bags. The buildup of carbon dioxide varied significantly with the treatment ($F_{3,12} = 64.11$; $P < 0.0001$; coefficient of variation = 0.94) and the storage period ($F_{3,36} = 199.43$; $P < 0.0001$; coefficient of variation = 0.94). The interaction between these two factors was also significant ($F_{9,36} = 104.03$; $P < 0.0001$; coefficient of variation = 0.96). The significant differences observed were explained by the interaction effects. During the first 60 days of storage, carbon dioxide levels increased, reaching a value of 15.7% for grains stored at 12% moisture content and thereafter declined marginally when SuperGrain IV-R™ bags became perforated by *P. truncatus* (Table 6). Overall, grains stored at 16 and 18% moisture contents recorded lowest (8.8%) and highest (15.6%) carbon dioxide levels (Table 6).

Table 6: Mean% (±SE) carbon dioxide levels within SuperGrain IV-R™ bags after 60, 120, and 180 days of storage.

Treatment	Storage period (days)			
	0	60	120	180
SGB IV-R™ + 12% MC grain	2.2 ± 0.1a	15.7 ± 0.4c	12.1 ± 0.7b	12.5 ± 0.9c
SGB IV-R™ + 14% MC grain	10.4 ± 0.3c	11.0 ± 0.4a	9.6 ± 0.8a	10.5 ± 0.3b
SGB IV-R™ + 16% MC grain	7.9 ± 0.1b	10.9 ± 0.3a	8.9 ± 0.4a	7.6 ± 0.4a
SGB IV-R™ + 18% MC grain	12.3 ± 0.3d	14.3 ± 0.4b	18.9 ± 0.1c	17.0 ± 0.9d
F value	521.02	41.17	49.46	48.31
P value	<0.001	<0.001	<0.001	<0.001

Means within a column followed by the same letter are not significantly different (SNK test, $P > 0.05$). SGB IV-R™: SuperGrain IV-R™ bag.

5. Discussion

5.1. Moisture Content and Grain Discolouration. Moisture content and temperature are among the most critical factors that affect the quality of grains during storage. The normal harvesting moisture content for most maize farmers in the tropics, particularly in Africa, is 18–20%. The ears are usually put into drying cribs to reduce the moisture content to around 14%, shelled and bagged. Maize is therefore stored while still relatively with high moisture content. The combined effect of warm temperatures and high moisture content results in accelerated grain deterioration and promotes growth of insects and fungi [30]. To maintain good quality maize during storage, grains must be protected from changes in moisture content and growth of insects and microorganisms such as fungi. This study demonstrated that moisture of maize grains stored in SuperGrain IV-R™ bag did not change over the whole storage period, indicating lack of exchanges between the SuperGrain IV-R™ bag and the outside environment. This suggests that the grains would not dry in the bag if not dried to safe moisture content level before storing. The finding confirms earlier study that showed the moisture content of grains stored in the hermetic bags remains unchanged during storage [31]. In contrast, because of permeability of polypropylene bags, grains lost moisture in response to ambient relative humidity. Among factors that influence insect infestation in grain storage ecosystem are water, temperature, and air [32, 33], and thus insect damage increases during storage.

The most common mould damage shows grain darkening symptoms. Safe grain storage is assessed by, among other factors, fungal growth, moisture content, and storage period. Infection of maize by storage fungi results in grain discolouration. Grain discolouration is a key factor for assessing the visual quality and market value. Kenya's maize standards and specifications KS01-143 ensure acceptable grain quality classification for producers, processors, and consumers. The standards which are harmonised with regional and international standards compare well with the South African and US corn specifications [34]. To facilitate marketing, maize grain is classified into four different grades, based on several factors. For the discoloured grains, the amount varies from 2% for grade 1 (K1) to 6% for grade 4 (K4). These grades attract different market prices. National Cereals and Produce Board (NCPB) whose core business constitutes commercial grain trading sells 90 kg bag of premier maize grain (grade 2) for human consumption at Ksh.2300 (USD 23) and Ksh.1400 (USD 14) for grade 4 for animal feed processing. This study showed that insignificant discolouration (2% up from 1.2% at the onset of the study) was only found with grains at 12% moisture content stored in SuperGrain IV-R™ bags 180 days after storage. The results are in agreement with [35] findings on storage studies on pinto beans under different moisture contents and temperature regimes. In contrast, grain discolouration in polypropylene bags reduced with storage period because discoloured grains that showed signs of insect damage (holes and/or tunnelling) were classified as damaged. From health view, consumption of grains with higher percentage of discolouration is a potential risk due to mycotoxin contamination such as aflatoxin produced by the moulds. Cases of aflatoxin poisoning are high in Kenya which is exacerbated by untested maize flour from local posho mills in the rural areas. It would be risky to store moist grains (14–18% moisture content) in hermetic bags due to higher grain discolouration that may result in loss of market price premium and because of associated health hazard due to fungal growth that produce mycotoxins if the grains enter the food chain. However, grain quality before storage will determine whether the grain will maintain quality during longer storage period. As grain moisture level greatly influences the type of moulds that infect and grow on grains, moisture content must therefore be reduced by drying to levels below that at which moulds grow (13%) within the storage environment under tropical conditions.

5.2. Sitophilus zeamais and Prostephanus truncatus Population. A significant reduction of *S. zeamais* and *P. truncatus* population when maize grains were stored in SuperGrain IV-R™ bags was demonstrated in this study. The prevailing mean ambient temperature (26°C) and relative humidity (54%) during the study were within the range for the development of both insect species. However, the population growth in the SuperGrain IV-R™ bags was low. The reduction could be attributed to carbon dioxide levels achieved within SuperGrain IV-R™ bags when properly tied. For effective control of storage pests, [36] showed that carbon dioxide level above 40% is required. In [37], it is reported that mortality of immature and adult insects rapidly increased when exposed to carbon dioxide levels of 7–19% and defined the level that would kill 95% *Tribolium castaneum* adult population as 20% in five days. Overall, carbon dioxide levels in the present study were maintained within 8–16% range, and the observed reduction in insect population probably could be attributed to high temperature (23–30°C) and lower relative humidity (46–58%) that enhanced insect metabolism and accelerated carbon dioxide toxicity. In the hermetic storage system, insect development is delayed and fecundity altered [31]. The reduction in insect population observed is consistent with the findings reported in [31] when maize was stored in PICS bags. PICS and SuperGrain IV-R™ bags are type of multilayer coextruded tougher plastics with low permeability of gas and good water barrier properties. The population growth of *S. zeamais* was higher than *P. truncatus* during the entire storage duration in polypropylene bags. Since *P. truncatus* was not artificially introduced into the grains, interspecific competition with *S. zeamais* probably affected its population increase [38].

5.3. Grain Weight Loss. The effectiveness of grain storage is greatly influenced by storage period and weight loss during storage duration. The weight loss levels observed in the bags are attributed to insect population in the bags. Maize grains stored in SuperGrain bags IV-R™ maintained very low weight loss (1–3%) compared to the equivalent grains in polypropylene bags (35–43%) at 180 days after storage. The weight loss levels were much lower than 13% which has been reported by DeGroote et al. [39]. The observed difference probably could be ascribed to differences in the evaluated SuperGrain bag types. In the present study, the used SuperGrain IV-R™ bag is an improved version of the one reported by [39]. The new SuperGrain IV-R™ bag is characterised by ultra-low oxygen permeability, greater toughness, and perforation resistance while retaining the original 0.078 mm thickness [28]. Higher losses were recorded in the grains stored in polypropylene bags. SuperGrain IV-R™ bags kept grains at 12% moisture content within the acceptable low weight loss level (1.2%). Similar observations have been reported under high levels of artificial infestation in the maize grain at similar moisture content stored in the SuperGrain bag [39] and PICS bag [31]. When the market supply cannot satisfy the demand, grains at 12% moisture content stored in SuperGrain IV-R™ bags would be sold at the highest price because of very low percentage of discoloured grains and weight loss thus contributing to improved livelihood income of the smallholder farmers.

5.4. Carbon Dioxide Levels. SuperGrain bag IV-R™ is a hermetic bag, and its mode of action in protecting the grain against insect pests is through composition of atmospheric gases rich in carbon dioxide and low in oxygen within the storage enclosure that suppress the ability of pests to develop and reproduce [40]. Insects die when the oxygen level in the air is reduced below 3% [20] and feeding activity stops when the level falls below 4% [41]. Although the carbon dioxide level in moist grains was higher, it did not exceed 20%. The results obtained from this study confirm the study in [3] which showed that the generation of carbon dioxide in grains at 14 and 16% moisture content under hermetic storage conditions did not exceed 20%. The apparent lack of hermetic conditions could have been caused by *P. truncatus* perforation of the bags, which probably facilitated gaseous exchange during storage between the outside environment and the inside of the bags. The holes were made by this pest from the outside source in the barn as it was not infested with the grains at the onset of the experiment. Perforation of the hermetic bags has been reported by Gracía-Lara et al. [28] when evaluating the effectiveness of SuperGrain IV-R™ bags and Kukom et al. [31] PICS bags for protection against insect pests in stored maize. In other studies in Niger, *Callosobruchus maculatus* Fabricius (Coleoptera: Bruchidae) was found to perforate PICS bags which are used for cowpea storage [42]. The other factor could be that the respiration of the grains, insects, and microorganism did not greatly contribute to the evolution of carbon dioxide.

6. Conclusion

The study confirms the effectiveness of SuperGrain IV-R™ bag as a storage method. Grains should be sorted and sieved to remove debris and broken grains to limit sources and development of insect pests and moulds. The initial grain moisture content remained unchanged, while in polypropylene bags, it reduced. Moist grains must be dried to lower level before storage for a longer period to avoid spoilage due to moulds and grain discolouration. The respiration of grains and insects in the bags did not contribute greatly to the evolution of carbon dioxide due to holes made in the bags by *P. truncatus*. This study was only carried out at one site; therefore, further study under cool, hot, and humid conditions is needed to confirm the findings.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The mention of trade names in this paper is only for the purpose of providing specific information and does not imply endorsement by KALRO, CIMMYT, ICIPE, and Kenyatta University. The views expressed in the study are solely the opinion of the authors.

Conflicts of Interest

The authors declare no conflicts of interest.

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