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ABSTRACT

Stored product insect pests cause significant losses in maize in sub-Saharan Africa (SSA). Control of these pests with conventional insecticides is fraught with health and environmental risks. Globally, several reduced-risk methods have been deployed as alternatives to conventional insecticides. In this study, conducted in February–December 2016, efficacies of five treatments to control insects in bagged maize stored in Nigerian market storehouses were evaluated. Treatments included a botanical (*Piper guineense*), Bularafa diatomaceous earth (DE), permethrin powder (Rambo™), PICS (hermetic) bags and ZeroFly® bags. The study also had a negative control comprising untreated maize in polypropylene bags. Study locations were in three grain markets, namely Eleekara market in Oyo town and Arisekola market in Ibadan, Oyo State, South West Nigeria, and Ago market in Ilorin, Kwara State, North Central Nigeria. Except in the case of PICS bags, each storehouse had six 100-kg bags for each storage method or treatment; these bags were sampled monthly. For PICS, each storehouse had 18 bags (~80 kg each) and six were destructively sampled every 4 months. Psocids (total 3,614) and *S. zeamais* (total 1,255) were the most abundant types of insects found during the study. However, among all treatments, PICS bags were the most effective at mitigating population growth of all species of stored product insects encountered, and the number of psocids and *S. zeamais* found in PICS bags during the entire study were 0 and 8, respectively. The order of effectiveness of the treatments were PICS > Permethrin > ZeroFly > DE > Botanical > control. Data showed PICS, Permethrin, ZeroFly, and DE when used according to manufacturer's instructions or label are effective and can be incorporated in integrated pest management of stored-product insects in maize storehouses. More research is required to explore how *P. guineense* can be made more efficacious.

1. Introduction

In sub-Saharan Africa (SSA), maize is both a staple and cash crop and contributes to stabilizing household incomes and alleviating poverty (Adetunji, 2007; Olaniyan, 2015). As a staple, it is fast replacing sorghum, millet and traditional starchy foods such as cassava in most communities in SSA (Olaniyan, 2015). Maize, particularly yellow maize, is rich in antioxidants (Thakkar and Failla, 2008), vitamins (Rocheford et al., 2013), essential minerals (Ullah et al., 2010) and dietary fibre (Schatzkin et al., 2007). Maize is also an important source of raw materials (Orhun, 2013) for production of ethanol fuel (Ranum et al., 2014) and livestock feed (Shi et al., 2014). Therefore, it is important to effectively preserve harvested maize in order to ensure food and financial security,

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availability of animal feed, seeds for planting and raw material for industries.

Storage pests, including insects, rodents, birds and microorganisms are major constraints in the maize value chain. However, insects are the most destructive pests of maize in Nigeria and other developing countries (Boxall et al., 2002). Stored maize is attacked by a number of internal feeders (primary stored-product insect pests) whose immature stages feed and develop inside whole kernels. Internal feeders are usually the first to attack harvested and stored maize (Ileleji et al., 2007). Examples of internal feeders are the maize weevil, *Sitophilus zeamais* (Motschulsky) (Coleoptera: Curculionidae), lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) and Angoumois grain moth, *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechidae). In sub-Saharan Africa, losses attributed to internal feeders have been estimated at 20–90% for maize with no insect management methods applied during storage (Tefera et al., 2011). These insect pests hollow out and perforate maize, encouraging infestation by external feeders (secondary stored-product insect pests) such as the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), saw-toothed grain beetle, *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae) and rust-red or rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Laemophloeidae). External feeders are not capable of infesting whole kernels but only feed on damaged kernels (Fekadu et al., 2012).

Management of insect pests in stored maize is of utmost importance and if not implemented can lead to significant losses within a few months of storage resulting in damaged kernels, reduced weight and nutritional value, reduced germination and low market value (Yuya et al., 2009; Mugo et al., 2015). Existence of only a limited number of cost-effective ways of controlling insect pests sometimes forces smallholder farmers to sell their grains early at throwaway prices during periods of glut (Stathers et al., 2008).

Since the 1950s, control of stored grain insect pests in SSA has largely been with the use of conventional synthetic insecticides, comprising mostly of petroleum-based contact organophosphate and pyrethroid compounds (Stathers et al., 2008). Grain fumigation with phosphine tablets (metal phosphides, phosphine gas, or hydrogen phosphide (PH_3)) is also widely practiced (Ojiako and Adesiyun, 2008). The grain industry is reducing its reliance on synthetic insecticides because of increasing governmental regulation (Fields et al., 2002), consumer concerns over insecticide residues (Abd El-Aziz, 2011) and development of resistance in insect populations (Odeyemi et al., 2010). Many organizations (including USDA, FAO and WHO) now promote non-chemical forms of pest-control with increasing focus on agriculture that is not solely pesticide reliant but oriented on integrated pest management practices (IPM) (Mvumi and Stathers, 2003).

In this study, reduced-risk stored-product insect pest management methods such as the West African Black Pepper (*Piper guineense* (Schum & Thonn)), Nigeria-derived Bularafa diatomaceous earth (DE), Purdue Improved Crop Storage (PICS) hermetic bags and ZeroFly® Storage Bags (hereafter referred to as ZeroFly or ZeroFly bags) were assessed for their efficacy against stored-product insect pests with a view toward incorporating them in integrated pest management programs. *Piper guineense* is a popular inexpensive cuisine spice; being a food condiment, it is considered safe, and has been used locally for post-harvest pest control in grains (Mahdi and Rahman, 2008). It is a climbing plant with more than 700 species throughout the tropical and subtropical regions of the world (Njoku and Ekenze, 2003). Diatomaceous earth (DE) is comprised of fossilized skeletal remains of diatoms (phytoplankton) which inhabited marine and fresh water bodies millions of years ago (Iatrou et al., 2010). DE is a potentially attractive alternative for Nigerian smallholder farmers because it has low mammalian toxicity, is inexpensive, locally available and does not require specialized equipment or skills for application (Vayias and Stephou, 2009; Nwaubani et al., 2014). Nigeria has discovered huge deposits of diatomite within its borders (Raw Materials Research and Development Council of Nigeria (RMRDC), 2009) and is launching massive exploitation for insecticide-related usage. A PICS bag comprises two layers of high-density polyethylene (PE) liners and a third layer of woven propylene (PP); this bag kills insects by creating an oxygen-deprived, hermetic environment (Baoua et al., 2012). A ZeroFly bag is a deltamethrin-incorporated polypropylene bag that prevents infestations by acting as a barrier against penetration by insects (Baban and Zivanovic, 2014). Deltamethrin is incorporated in the individual yarns of the ZF bag fabric and is slowly released onto the surface of the yarn in a sustained manner (Vestergaard, 2014).

Although the stored-product insect pest management methods in this study are being used to varying extents in different parts of SSA (Baoua et al., 2014; Mutambuki et al., 2014; Amadou et al., 2016), there is a dearth of information on how effective these technologies are under field conditions in storehouses located in grain markets in Nigeria, specifically in North Central and South West Nigeria. Therefore, the objective of this study was to evaluate five stored-product insect pest management methods — a botanical (*P. guineense*), diatomaceous earth (Bularafa DE), permethrin powder (Rambo™), PICS hermetic bags and ZeroFly bags — for their effectiveness in reducing insect population growth in maize stored in storehouses located in grain markets in North Central and South West Nigeria.

2. Materials and methods

2.1. Study sites

This study was conducted during the period February–December 2016. Four storehouses (11 m × 8 m) located in three grain markets namely, Ago market in Ilorin Kwara State, North Central Nigeria (8°29′34.8″N 4°32′59.9″E), Eleekara market in Oyo town, Oyo State, Southwest Nigeria (7°49′50.7″N 3°54′39.5″E) and Arisekola market in Ibadan, Oyo State, Southwest Nigeria (7°26′08.3″N 3°54′46.1″E) were used. In Ago market, there were 2 storehouses, Ago 1 and Ago 2. Eleekara and Arisekola markets were ~46.9 km apart. Ago 1 and Ago 2 storehouses were ~10 m apart. The distances between Ago market and the other two markets, Arisekola and Elekaara, were ~164 km and 113 km, respectively. The study was purposely set up in grain markets partly because external infestation from other non-study storehouses was highly likely and expected to be substantial.

2.2. Maize

A yellow maize variety known as SWAN 2 was used for this study. The maize (37 MT) was obtained from Ijaye Farm Settlement in Akinyele Local Government Area, Ibadan Oyo State. Farmers in the settlement had applied Aflasafe™ in fields used to produce maize for this study. Aflasafe contains a mixture of four atoxigenic strains of *Aspergillus flavus* that were obtained in Nigeria. A single application of aflasafe was broadcast on fields at a rate of 10 kg/ha, 2–3 weeks before flowering of the crop (ATTC, 2018). Initial maize moisture content (MC) was checked on-farm (John Deere Moisture Chek-Plus Grain Moisture Tester – SW08120, Deere and Company, Moline, IL, USA) and determined as 9.1%.

2.2.1. Maize fumigation

Maize was fumigated before use to minimize transfer of insect pests from field to storehouse. Fumigation was conducted at the Nigerian Stored Products Research Institute (NSPRI), Ilorin, Kwara State, Nigeria, in a building with large windows and doors. During fumigation, maize was stored in jute bags that were placed on wooden pallets (1.23 m × 1.23 m). The bags were arranged in 5 stacks; two were 12 m × 1.6 m x 1.7 m and three were 10.5 m × 1.6 m x 1.7 m 'Force Toxin' brand of Phostoxin® tablets (Sino Agro Chemical Industry Limited, Guangdong, Gubo Town, Nanjiang, Jiangsu, China) was used for fumigation. The number of aluminium phosphide tablets used for fumigation was calculated based on the label recommendation of 2–3 tablets/m^3; for this study, a rate of 2.5 tablets/m^3 (1,785 parts per million) was used. Tablets were placed in 9-cm disposable Petri dishes; 4–6 tablets were placed in each dish and dishes were evenly distributed under each stack. Stacks were covered with leak proof tarpaulins (fumigation sheets; 16.8 m × 3.0 m) with approximately 1 m overhang on the floor around the stack, and sand snake bags were placed on the overhang to properly seal the stacks. Each tarpaulin had a rope attached to its end to facilitate removal from outside the building after fumigation. After 7 days, windows and doors were opened and tarpaulins removed through the windows. The building was ventilated for 3 days and phosphine levels were checked using a digital meter (Dräger Pac® 7000 Single Gas Detector, Draegerwerk AG & Co. KGaA, Moislinger Allee, Lübeck, Germany) to make sure the concentration was below 0.3 ppm before re-entering the building.

2.3. Storage methods (treatments)

Six storage treatments in this study comprised of ZeroFly® bags, PICS bags, diatomaceous earth (Bularafa DE) (hereafter referred to as DE), botanical (*P. guineense*) (hereafter referred to as Botanical) and permethrin (Rambo™) (hereafter referred to as Permethrin), and a negative control comprising of untreated maize in polypropylene bags (hereafter referred to as Control).

2.3.1. ZeroFly® storage bag

In each storehouse, there were six 100-kg ZeroFly bags (Vestergaard Frandsen Vietnam, Hanoi, Vietnam) of maize arranged in a horizontal pattern on a single wooden pallet. During 11 months of the study, all six bags were sampled monthly. Disposable nitrile gloves were worn in setting up the ZeroFly treatment.

2.3.2. Purdue Improved Crop Storage (PICS) bag

Each storehouse had eighteen 100-kg PICS bags (Lela Agro Industries Nigeria Limited, Kano, Kano State, Nigeria), each containing 80 kg of maize, arranged on four pallets. Bags on pallets were arranged to form two layers of nine bags. The procedures recommended by Purdue University PICS team for using PICS bags were followed (Baributsa et al., 2015). These procedures involved storing properly dried corn (MC of ≤13%), checking that inner liners were not punctured before use, checking the integrity of the outer liner, and ensuring that bags were properly sealed.

2.3.3. Diatomaceous earth (DE)

Crude DE ore of fresh water origin was obtained from Bularafa community in Yobe State, Northern Nigeria. It was oven dried at 40 °C to 4.5% MC (Arnaud et al., 2005), ground to dust by means of a laboratory mortar and pestle, sieved using an Endecott sieve of 90 μm openings and kept in air-tight Kilner jars prior to use. Information on DE particle sizes can be found in Otitodun et al. (2015). Each storehouse had six 100-kg bags containing maize that was properly admixed with DE at a rate of 1,000 ppm (100 g/100 kg) (Nwaubani et al., 2014) in 50-L plastic basins. After mixing by hand in the basins, the DE-treated maize was poured into 100-kg polypropylene bags and sewn using a portable filled bag-closing machine (Model: GK26-1A). Disposable hand gloves and dust masks were worn during admixing by hand. The bags in each storehouse were arranged on one wooden pallet. All six bags in each storehouse were sampled every month.

2.3.4. Piper guineense (African Brown Pepper)

Ripe fruits of *P. guineense* were obtained from a farm in Oro kingdom, Ondo State, South West Nigeria. The fruits were thinly spread on a table under shade to dry (Okonkwo and Okoye, 2001). They were then moved into a laboratory oven set at 30 °C to dry adequately (Donald et al., 2008). Thereafter, the dried fruits were ground to powder with a laboratory electric blender, sieved using an Endecott sieve of 90-μm openings and kept in airtight Kilner jars prior to use. Maize containing 15,000 ppm of *P. guineense* was obtained by separately admixing 1,500 g of *P. guineense* (Otitodun et al., 2015) with 100 kg of maize in 50-L plastic basins. After mixing by hand, the *P. guineense*-treated maize was poured into 100-kg polypropylene bags and sewn using a portable bag closing machine (Model: GK26-1A). Disposable hand gloves and dust masks were worn during admixing by hand. All six bags in each storehouse were sampled every month.

2.3.5. Permethrin (Rambo™ insect powder)

Rambo brand insect pest protectant powder comprises 0.6% permethrin and 99.4% inert carriers (Gongoni Company Limited, Kano, Kano State, Nigeria). Permethrin powder was assessed as comparative check (positive control). Each storehouse had six 100-kg bags containing maize which was properly admixed with Rambo at a rate of 167 g/100 kg, i.e. permethrin concentration in maize was 10 ppm. Maize containing 10 ppm of permethrin was obtained by separately mixing 167 g of Rambo with 100-kg maize in 50-L plastic basins. Thereafter, the Rambo-treated maize was poured into 100-kg polypropylene bags and sewn using a portable bag closing machine (Model: GK26-1A); in each storehouse the bags were placed on one wooden pallet. Disposable hand gloves and dust masks were worn during admixing by hand. All six bags in each storehouse were sampled every month.

2.3.6. Untreated control

The Control (negative control) was comprised of untreated maize in untreated 100-kg polypropylene bags. No insect pest-control measure was associated with the Control bags during the 11-month study. The bags were sewn using a portable bag closing machine (Model: GK26-1A) and arranged on one wooden pallet. All six bags in each storehouse were sampled every month.

2.4. Experimental design

Shelled maize that was stored in specialized bags (PICS and ZeroFly), admixed with a protectant (DE, *P. guineense* or permethrin) in polypropylene bags and untreated maize in polypropylene bags (Control) was transported to each market. In each storehouse six, 100-kg maize-filled bags were assigned to each of the following treatments: ZeroFly, DE, Botanical, Permethrin and Control treatments. A stack of six bags for each treatment was on a separate pallet to prevent bags from absorbing moisture from the concrete floor. Eighteen bags assigned to the PICS treatment were arranged on four pallets, and bags on pallets were arranged in such a way that they formed two layers. The pallets for each treatment were placed 1 m apart from each other. There were forty-eight bags per storehouse. Additionally, a minimum of six mouse-gum traps (HANA High Quality Glue Board, P.M. Hana (HK) Ltd., Hong Kong,

China) were placed in each storehouse to minimize rodent damage to bags of stored maize. Presence of mice had been detected during preparation of storehouses for the experiment. Mice traps were replaced once a month, during sampling of maize in the bags. A temperature and relative humidity data logger (HOBO U12, Onset Computer Corporation, Bourne, MA, USA) was hung from the ceiling inside and outside the storehouses to record temperature and relative humidity values at 1-h intervals.

The experimental design for this study was a randomized complete block design (RCBD) with four replications (number of storehouses) and six sub-replications (number of 100-kg bags sampled during each sampling event).

2.5. Sampling and data collection

Temperature, relative humidity (RH) and MC of maize in each bag sampled were determined using the GrainMate moisture meter (Armstrong et al., 2017; Sesi Technologies, Kumasi, Ghana). Samples of maize were obtained using a 1.2-m open-ended Trier (grain probe) (Seedburo Equipment, Chicago, IL, USA) with six openings. The trier was inserted into a bag of maize in closed position, opened after it was properly inserted and closed when full, before it was pulled out. Maize in the trier was emptied into a 2-L Ziploc bag through the open end of trier, and thereafter, taken into the laboratory for processing. Samples were taken twice from each 100-kg bag. Each trier sample weighed ~350 g; hence a total of 700 g was taken from each bag during each sampling event. A small opening of about 3 cm wide was made at the seam area of every bag to accommodate insertion of the trier during sampling. The incision made on the bag was sealed using tape (Duct Tape™) which facilitated easy opening and closing of the bags during subsequent sampling. All the six bags assigned to each non-PICS treatment in each storehouse were sampled during each sampling event.

In the PICS treatment, six bags were destructively sampled every 4 months. The six bags to be sampled during each sampling event had randomly been selected at the beginning of the study. Each of the PICS bags was opened and two trier samples were taken using a similar protocol to that described above. Sampled bags were removed from the storehouse as they were no longer needed. Samples were obtained from each bag because it was neither practical nor economical to examine all the maize in each bag. Because all the maize in each of the six bags sampled for each treatment, during each sampling event, was not examined, this is bound to affect the accuracy of our results.

2.6. Grain quality variables (%IDKNB, %WL and %DG)

To estimate insect damaged kernels (IDK) by numerical basis, weight loss and maize discoloration, a 250-g sub-sample was used from the 700-g samples collected. These variables were then calculated as described below.

2.6.1. Insect damaged kernels (%) per 250-g sample

The percentage of insect damaged kernels by number basis (% IDKNB) was determined by pouring each 250-g sample on a tray and all kernels were examined using a hand lens (10× magnification). Kernels with holes created by insects were separated from the undamaged kernels and the number of kernels in each category recorded. The %IDKNB was estimated monthly based on total number of kernels in 250 g of each sample. The %IDKNB was calculated using the formula below:

$$\%IDKNB = \frac{Number\ \ of\ \ IDK}{Total\ number\ \ of\ \ kernels} \times 100$$

2.6.2. Weight loss (%) per 250-g sample

Weight loss due to insect damage was calculated using the count and weigh method (Gwinner et al., 1996) and the equation:

$$\%WL = \frac{[(Wu * Nd) - (Wd * Nu)]}{Wu * (Nd + Nu)} * 100$$

where Wu is the weight of undamaged kernels (grain), Nu is the number of undamaged kernels, Wd is the weight of damaged kernels, and Nd is the number of damaged kernels.

2.6.3. Maize discoloration per 250-g sample

The number of discolored maize kernels was also determined monthly based on each 250-g sub-sample. Each sub-sample was poured on a round stainless steel tray, discolored kernels were separated from non-discolored kernels and their number recorded. Kernels that are materially discolored and/or whose natural color has been altered by external factors such that they appear stained are referred to as discolored kernels (GSA, 2013).

Percent kernel discoloration (%DG) was calculated using the formula below:

$$\%DG = \frac{Number\ \ of\ \ discolored\ \ kernels}{Total\ number\ \ of\ \ kernels\ in\ \ 250\ \ g} \times 100$$

2.7. Seed germination

In order to assess the viability of seeds every month, a germination test was conducted using 120 randomly selected seeds from the monthly samples (700 g) from each bag. Seeds were placed on moistened filter papers (Whatman No.1) in 9-cm disposable Petri dishes, which were re-wetted with 3 ml of water every 3 days when required (Rao et al., 2006). There were 20 seeds per dish and all dishes were arranged randomly on a laboratory bench. The number of seeds that germinated was recorded after 7 days.

Percentage seed germination was calculated using the formula of Adedire & Akinkurolere (2005):

$$Germination\ \ (\%) = \frac{Number\ \ of\ \ germinated\ \ seeds}{Total\ \ number\ \ of\ \ seeds} \times 100$$

2.8. Aflatoxin

Five-gram samples were taken from the 250-g samples described above for estimation of aflatoxin levels using VICAM AflaV™ test kit in accordance with manufacturer's specifications. All samples were processed at NSPRI in Ilorin and University of Ibadan (UI), Ibadan, Oyo State.

2.9. Data analysis

The experimental design was a randomized complete block design (RCBD) with sub-replication. Statistical analyses were performed with SAS Version 9.3 (SAS Institute, Cary, NC). Treatment effects were assessed using analysis of variance methods (PROC MIXED). A repeated measures model in a randomized complete

block design was utilized, with storehouse as the blocking factor and month as the repeated factor. Analyses of the numbers of live insects were conducted with the use of a square root transformation where necessary. The simple effects of treatment in a given month were assessed with protected planned contrasts (SLICE option in an LSMEANS statement). Additionally, the SLICE option was used to assess simple effects of month in a given treatment. Percentage data analyses were conducted with the use of an arcsine transformation to stabilize variances but untransformed percentages are reported. Data for the 4 months when PICS bags were sampled were analysed separately from those of other months when they were not sampled. However, in the latter case, the December data were included in the analysis to show effectiveness of each of the five treatments in the final month of the study. Number(s) of insects when used in reference to data from this study refers to number of insects per 700 g (insect density), and total number of insects refers to sum of all insect numbers.

Correlations between total number of live insects and numbers of *S. zeamais*, *P. truncatus*, *R. dominica*, *S. cerealella*, *C. ferrugineus*, *T. castaneum*, *O. surinamensis* and psocids (booklice) with %IDKNB, % WL, %DG, temperature, RH, or MC were conducted using the Correlation Procedure of SAS, at $P < 0.05$.

3. Results

3.1. Temperature, moisture content and relative humidity

Temperatures inside the buildings that comprised replications 1, 2, 3 and 4 at Ago 1, Ago 2, Arisekola, and Eleekara markets during the 11 months of the experiment ranged between 25.5 and 35.7, 25.3–34.0, 25.8–33.1, and 26.3–33.4 °C, respectively. This corresponded to means of 29.8, 30.0, 28.8 and 29.7 °C, respectively. For RH, values ranged between 36.8 and 56.4, 34.0–74.1, 35.3–75.9 and 36.8–72.2%, respectively. This corresponded to means of 56.4, 56.5, 60.8 and 57.6%, respectively. Grain moisture content values ranged between 6.5 and 14.6, 6.2–14.7, 8.3–15.1 and 8.5–14.7%, respectively. This corresponded to means of 11.3, 11.3, 12.4 and 11.8%, respectively. Corresponding equilibrium moisture content levels were 11.5%, 11.5%, 12.3% and 11.7%, respectively, based on average temperature and RH values.

3.2. Number of insects per 700 g of maize for all six treatments

The focus of the results presented is the 4 months when PICS bags were sampled, i.e. February, June, October, and December (Tables 1 and 2). Results for the other 7 months, with December included, are referred to on occasion in order to provide perspective and improve clarity (Tables 3 and 4).

The most abundant primary insect pest found was *S. zeamais* whereas the predominant secondary pests were *C. ferrugineus, O. surinamensis* and *Liposcelis* spp. ('Psocoptera' — Psocodea: Liposcelididae). *Liposcelis* spp. are hereafter referred to as psocids. Data for only the four types of insects above with the most abundance and which also had densities of >2 insects per 700 g of maize in at least one sample collected are reported. *Sitophilus zeamais* (total 1,255), *C. ferrugineus* (total 1,138), *O. surinamensis* (total 1,039), and psocids (total 3,614) were found during the study. Other insects found during the study were *T. castaneum* (total 253), *R. dominica* (total 204), *P. truncatus* (total 54), *Plodia interpuntella* (Hübner) (Lepidoptera: Pyralidae) (total 118) and *S. cerealella* (total 874). All treatments had no infestation detected during the period February–April 2016 (Tables 2 and 4). Psocids (1.4) were the first insects detected in May and were found in the Control (Table 4). In June, *C. ferrugineus* (0.4) and *O. surinamensis* (1.5) were first detected in the Control, and psocids (0.5) were detected in the Permethrin treatment the same month (Table 2). In the July–December period, insect numbers were generally higher than those found in May and June for all treatments (Tables 2 and 4).

In the case of *S. zeamais* the main effects treatment and month and their interaction were significant (Table 1). "Treatment" in this case refers to the five pest management methods and the Control. In October, only the Botanical (0.1), Control (7.0) and PICS (0.2) treatments had *S. zeamais* (Table 2). However, *S. zeamais* was first detected in only the Control in September (1.0) (Table 4). In December, there was significant increase in density in the control to 18.9; in the ZeroFly treatment, a density of 4.3 was found in December. Also, in December, Botanical, DE, PICS and Permethrin treatments had densities of 3.5, 1.3, 0.2, and 0.7, respectively (Table 2). In the PICS treatment, *S. zeamais* was found in just one specific bag in Arisekola market.

In relation to live *C. ferrugineus*, the main effect treatment, was not significant ($P > 0.05$) (Table 1). However, month and month-treatment interaction were significant (Table 1). *Cryptolestes ferrugineus* was first detected in the Control in June (0.4) (Table 2). In October, a density of <1 was found in all treatments except in the botanical and control where densities were 1.8 and 3.7, respectively (Table 2). However, the numbers of insects in all treatments in October were similar. In December, *C. ferrugineus* population density was significantly higher in the Botanical (7.7) and Control (11.1) when compared with other treatments which had densities ≤ 2 (Table 2). The PICS treatment had no insects found in December.

Regarding *O. surinamensis*, a similar pattern as in *C. ferrugineus* was observed with the main effect treatment not being significant but month and month-treatment interaction were significant (Table 1). *Oryzaephilus surinamensis* was first found only in the control (1.5) in June. The highest number of *O. surinamensis* (4.0) was found in the Botanical treatment in October.

In December, insect densities in the control, DE and Permethrin treatments were not different but numbers in the control (2.9) and DE (2.6) were significantly higher than in the rest of the treatments (Table 2). In December, Permethrin and ZeroFly had densities of 1.1 and 0.2, respectively, whereas no insects were found in the PICS and Botanical treatments (Table 2).

Similar to *S. zeamais*, the main effects treatment and month and their interaction were significant for psocids (Table 1). Psocids were first found in May in the Control (1.4) (Table 4). In the various treatments, psocids were not found or their numbers were generally low (<1) until October and December when numbers increased; the surge in population was most pronounced in the DE

Table 1
ANOVA for main effects Treatment (Trt) and Month (Mon), and interactions (*) for *Sitophilus zeamais*, *Cryptolestes ferrugineus*, *Oryzaephilus surinamensis*, and *Liposcelis* spp. (psocids) in 700 g samples of maize from Arisekola, Eleekara, Ago 1 and Ago 2 storehouses for the months of February, June, October and December 2016. Treatments comprised Botanical, Control, diatomaceous earth (DE), PICS bags, permethrin (Permethrin), ZeroFly® bags for maize samples taken in February, June, October, and December when PICS bags were destructively sampled.

Variable	Source	df	*F*	*P*
S. zeamais	Trt	5, 15.1	4.21	0.0136
	Mon	3, 183	11.25	<0.0001
	*	15, 189	3.82	<0.0001
C. ferrugineus	Trt	5, 18	1.39	0.2757
	Mon	3, 172	10.75	<0.0001
	*	15, 174	2.86	0.0005
O. surinamensis	Trt	5, 15	0.69	0.6410
	Mon	3, 170	4.68	0.0036
	*	15, 171	4.04	<0.0001
Liposcelis spp.	Trt	5, 15	8.25	0.0006
	Mon	3, 172	34.05	<0.0001
	*	15, 173	7.40	<0.0001

Table 2
Mean number of *Sitophilus zeamais* (Sz), *Cryptolestes ferrugineus* (Cf), *Oryzaephilus surinamensis* (Os), and *Liposcelis* spp. (Lp) (means ± SEs) in 700 g samples of maize from Arisekola, Eleekara, Ago 1 and Ago 2 storehouses for the months of February (Feb.), June (Jun.), October (Oct.) and December (Dec.) 2016. Significant differences among treatments for each month are denoted with different lower-case letters and differences among months for each treatment are denoted by different upper-case letters, ($P < 0.05$). If there are no upper-case letters in a column there were no significant differences among months ($P \geq 0.05$).

	Mon	Botanical	Control	DE	PICS	Permethrin	ZeroFly
Sz	Feb.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Jun.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Oct.	0.1 ± 0.1 aA	7.0 ± 2.1bB	0.0 ± 0.0 aA	0.2 ± 0.2a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Dec.	3.5 ± 1.2bB	18.9 ± 4.1 cC	1.3 ± 0.5abB	0.2 ± 0.2a	0.7 ± 0.4a	4.3 ± 1.7abB
Cf	Feb.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a
	Jun.	0.0 ± 0.0 aA	0.4 ± 0.2 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a
	Oct.	1.8 ± 0.8 aA	3.7 ± 1.2 aA	0.1 ± 0.1a	0.0 ± 0.0a	0.3 ± 0.2a	0.0 ± 0.0a
	Dec.	7.7 ± 2.4bB	11.1 ± 3.7bB	0.7 ± 0.5a	0.0 ± 0.0a	0.3 ± 0.2a	2.0 ± 1.7a
Os	Feb.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a
	Jun.	0.0 ± 0.0 aA	1.5 ± 0.7aAB	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a
	Oct.	4.0 ± 1.7bB	0.9 ± 0.3 aA	0.0 ± 0.0 aA	0.2 ± 0.2a	0.0 ± 0.0a	0.1 ± 0.1a
	Dec.	0.0 ± 0.0 aA	2.9 ± 0.9bB	2.6 ± 1.3bB	0.0 ± 0.0a	1.1 ± 0.6 ab	0.2 ± 0.1a
Lp	Feb.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0 aA	0.0 ± 0.0 aA
	Jun.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.5 ± 0.3 aA	0.0 ± 0.0 aA
	Oct.	2.3 ± 0.9bB	3.4 ± 0.9bB	13.7 ± 2.3 dB	0.0 ± 0.0a	6.3 ± 1.9 cC	2.3 ± 0.7bB
	Dec.	0.2 ± 0.1 aA	5.2 ± 1.4 cB	11.7 ± 2.2 dB	0.0 ± 0.0a	1.3 ± 0.5abB	1.6 ± 0.8abB

Table 3
ANOVA for main effects Treatment (Trt) and Month (Mon), and interactions (*) for *Sitophilus zeamais*, *Cryptolestes ferrugineus*, *Oryzaephilus surinamensis*, and *Liposcelis* spp. in 700 g samples of maize from Arisekola, Eleekara, Ago 1 and Ago 2 storehouses for the months of March, April, May, July, August, September, November and December 2016. Except for December, these were months when PICS bags were not destructively sampled. Treatments comprised Botanical, Control, diatomaceous earth (DE), permethrin (Permethrin), and ZeroFly® bags (non-PICS treatments).

Variable	Source	df	*F*	*P*
S. zeamais	Trt	4, 12.5	3.88	0.0288
	Mon	7, 309	28.35	<0.0001
	*	28, 313	5.37	<0.0001
C. ferrugineus	Trt	4, 12	1.18	0.3668
	Mon	7, 302	11.48	<0.0001
	*	28, 302	2.87	<0.0001
O. surinamensis	Trt	4, 12	2.34	0.1136
	Mon	7, 300	16.73	<0.0001
	*	28, 300	5.92	<0.0001
Liposcelis spp.	Trt	4, 12	1.49	0.2653
	Mon	7, 343	6.97	<0.0001
	*	28, 343	1.77	0.0104

treatment (Table 2). Psocids were not found in the PICS treatment throughout the study (Table 2). The DE treatment had the highest densities in October (13.7) and December (11.7), followed by Permethrin powder with 6.3 and 1.3, respectively. The control had 3.4 and 5.2 in October and December, respectively. Other treatments had densities ≤2.3, but as noted previously, PICS had none during the February–December period (Table 2).

3.3. Number of insects per 700 g of maize in non-PICS treatments

Numbers of insects for the different species for seven other months when sampling occurred but not previously presented in detail (when PICS bags were not sampled), and for December (final month of sampling) show a similar trend of increase in insect numbers from July to December (Tables 3 and 4). It is in May when psocids are first detected (Table 4), but numbers of all species then generally tend to increase from this point on until December when the study ended (Table 4).

Differences in numbers among treatments occur in the July–December period when populations of the various species appreciably increase in the Botanical, Control, and ZeroFly treatments (Table 4). Similarly, differences among months for the various treatments occur mostly due to appreciable increase in numbers that occur during the October–December period in the Botanical, Control, and ZeroFly treatments (Tables 2 and 4).

3.4. Grain quality variables %IDKNB, %WL, and %DG

In the case of %IDKNB, the main effects treatment and month and their interaction were significant (Table 5). In all treatments except PICS, %IDKNB in February was always lower than in December (Table 6). It was only in December when there were differences in %IDKNB among treatments; the highest value of 1.4 was found in the Control.

In relation to %WL, the main effects treatment and month and their interaction were significant (Table 5). In all treatments except PICS, %WL in February was always lower than that in October and/or December (Table 6). Highest %WL values were found in the Botanical and Control treatments in December and these were 0.3 and 0.4%, respectively. It was only in December when there were differences in %WL among treatments; the highest value of 0.4 was found in the Control.

Similarly, for %DG, the main effects treatment and month and their interaction were significant (Table 5). In most cases, %DG in February was lower than that in October and/or December (Table 6). Differences in %DG were observed among treatments in June, October, and December.

3.5. Germination

In relation to %GERM, the main effects treatment and month and their interaction were significant (Table 5). The only differences in germination among treatments occurred in October and December (Table 6). In relation to germination in February when compared to December, it slightly increased in the Permethrin treatment (92.4–97.1), remained similar in DE (95.1 and 96.3), Botanical (95.0 and 96.7), PICS (96.8 and 98.4), and ZeroFly (95.3 and 96.8) treatments, and decreased in the Control (97.3–88.1) (Table 6).

3.6. Aflatoxin

In the case of aflatoxin levels, ANOVA results for main effect treatment and month-treatment interaction were not significant (Table 5). However, month was significant (Table 5). Except in the ZeroFly treatment where aflatoxin levels were similar at the start and end of the study, levels in February were always lower than in

Table 4
Mean number of *Sitophilus zeamais* (Sz), *Cryptolestes ferrugineus* (Cf), *Oryzaephilus surinamensis* (Os) and *Liposcelis* spp. (Lp) (means ± SEs) in 700 g samples of maize from Arisekola, Eleekara, Ago 1 and Ago 2 storehouses for the months of March (Mar.), April (Apr.), May, July, August (Aug.), September (Sep.), November (Nov.) and December (Dec.) 2016. Significant differences among treatments for each month are denoted with different lower-case letters and differences among months for each treatment are denoted by different upper-case letters, ($P < 0.05$). If there are no upper-case letters in a column there were no significant differences among months ($P \geq 0.05$).

	Month	Botanical	Control	DE	Permethrin	ZeroFly
Sz	Mar.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Apr.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	May	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	July	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Aug.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Sep.	0.0 ± 0.0 aA	1.0 ± 0.8 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Nov.	1.5 ± 1.2aAB	11.3 ± 3.2bB	0.1 ± 0.1a	0.3 ± 0.3a	0.1 ± 0.1 aA
	Dec.	2.5 ± 0.9 aB	16.7 ± 4.2bC	1.2 ± 0.5a	0.7 ± 0.4a	4.3 ± 1.7 aB
Cf	Mar.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Apr.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	May	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	July	0.0 ± 0.0 aA	1.2 ± 0.7 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Aug.	0.0 ± 0.0 aA	2.3 ± 1.4 aA	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Sep.	0.6 ± 0.3 aA	4.2 ± 2.2aAB	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0 aA
	Nov.	3.9 ± 1.5abB	6.4 ± 2.4bB	0.0 ± 0.0a	0.7 ± 0.5a	0.0 ± 0.0 aA
	Dec.	7.7 ± 2.4bC	11.1 ± 3.7bC	0.7 ± 0.5a	0.3 ± 0.2a	2.0 ± 1.7aAB
Os	Mar.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a
	Apr.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a
	May	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a
	July	0.2 ± 0.1 aA	2.3 ± 0.9bB	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.1 ± 0.1a
	Aug.	0.8 ± 0.3abAB	2.5 ± 0.8bB	0.0 ± 0.0 aA	0.1 ± 0.1 aA	0.0 ± 0.0a
	Sep.	1.7 ± 0.8abB	2.3 ± 0.7bB	1.5 ± 0.4abB	2.0 ± 0.5abB	0.1 ± 0.1a
	Nov.	8.4 ± 2.0 dC	6.4 ± 0.8 cC	1.5 ± 0.5bB	0.2 ± 0.1 aA	0.0 ± 0.0a
	Dec.	0.0 ± 0.0 aA	2.9 ± 0.9bB	2.6 ± 1.3bC	1.1 ± 0.6abAB	0.2 ± 0.1a
Lp	Mar.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA
	Apr.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA
	May	0.0 ± 0.0 aA	1.4 ± 0.7aAB	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA
	July	7.0 ± 3.0abB	10.3 ± 2.6bD	4.7 ± 1.7abB	1.9 ± 0.7 aB	14.7 ± 12.4bB
	Aug.	3.1 ± 1.1abB	1.4 ± 0.7aAB	6.0 ± 1.6bB	1.3 ± 0.5aAB	5.1 ± 2.9abB
	Sep.	2.9 ± 1.0abB	1.5 ± 0.5aABC	10.8 ± 2.4 cC	4.0 ± 0.5bC	3.6 ± 1.0abB
	Nov.	2.3 ± 1.1abAB	2.0 ± 0.6abBC	13.4 ± 1.7 cC	4.0 ± 1.1bBC	0.6 ± 0.2 aA
	Dec.	0.2 ± 0.1 aA	5.2 ± 1.4bCD	11.7 ± 2.2 cC	1.3 ± 0.5abAB	1.6 ± 0.8abAB

Table 5
ANOVA for main effects Treatment (Trt) and Month (Mon), and interactions (*) for Percent insect damaged kernels by number (%IDKNB), percent weight loss (%WL), percent discolored kernels (%DG), percent germination rate (%GERM) and aflatoxin contamination (AFLA) in maize samples from Arisekola, Eleekara, Ago 1 and Ago 2 storehouses. Treatments comprised Botanical, Control, diatomaceous earth (DE), PICS bags, permethrin (Permethrin) and ZeroFly® bags for maize samples taken in February, June, October, and December when PICS bags were destructively sampled. Aflatoxin levels were estimated only in February and December.

Variable	Source	df	*F*	*P*
% IDKNB	Trt	5, 15	5.81	0.0035
	Mon	3, 161	43.88	<0.0001
	*	15, 162	4.07	<0.0001
% WL	Trt	5, 15	4.30	0.0127
	Mon	3, 160	22.43	<0.0001
	*	15, 161	2.53	0.0021
% DG	Trt	5, 18	3.06	0.036
	Mon	3, 198	99.98	<0.001
	*	15, 198	2.21	0.0073
% GERM	Trt	5, 15	3.35	0.0314
	Mon	3, 176	9.26	<0.0001
	*	15, 177	3.68	<0.0001
AFLA	Trt	5, 15	0.44	0.8104
	Mon	1, 18	58.81	<0.0001
	*	5, 18	1.25	0.3268

December in all other treatments. However, the highest level found in both February and December was 1.6 ppb, which is below the 20 ppb threshold recommended by United States Food and Drug Administration (USFDA) (United States Department of Agriculture (USDA), 2015).

3.7. Correlations

Correlation of insect numbers with temperature occurred only for psocids (Table 7). Total number of live insects and numbers of *S. zeamais*, *P. truncatus*, *C. ferrugineus*, *T. castaneum*, and *O. surinamensis* were all correlated with %IDKNB or %WL (Table 7). Total number of live insects and numbers of *O. surinamensis* and psocids were correlated with RH or MC (Table 7). In no case were insect numbers correlated with %DG. *Rhyzopertha dominica* and *S. cerealella* had no correlation with any of the variables hence were not included in Table 7.

4. Discussion

All treatments were without insects until 3 months into storage (May) when they were detected. Insects were detected for the first time in the Control. The period February–June corresponds to the dry season in areas where the study was conducted. This delay in infestation could be due to the effective fumigation conducted prior to maize storage; insect populations had to build up from very low numbers that may have survived fumigation or entered the bags. The relatively low initial grain MC (9.1%) of the maize going into storage could have also slowed down insect population growth. This lack of insects during the February–May period seems to show that storing low MC maize and effective PH_3 fumigation prior to

Table 6
Percent insect damaged kernels by number (%IDKNB), percent weight loss (%WL), percent discolored kernels (%DG), percent germination rate (%GERM) and aflatoxin contamination (AFLA) (means ± SEs) in samples of maize from Arisekola, Eleekara, Ago 1 and Ago 2 storehouses for the months of February (Feb.), June (Jun.), October (Oct.) and December (Dec.) 2016. Aflatoxin levels were estimated only in February and December. Significant differences among treatments for each month are denoted with different lower-case letters and differences among months for each treatment are denoted by different upper-case letters, ($P < 0.05$). If there are no upper-case letters in a column there were no significant differences among months ($P \geq 0.05$).

	Mon	Botanical	Control	DE	PICS	Permethrin	ZeroFly
% IDKNB	Feb.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.1 ± 0.0 aA
	Jun.	0.5 ± 0.1bB	0.3 ± 0.1abB	0.2 ± 0.0abB	0.1 ± 0.0aBC	0.2 ± 0.0abB	0.4 ± 0.1abB
	Oct.	0.5 ± 0.1abB	0.6 ± 0.1abC	0.3 ± 0.1aBC	0.3 ± 0.1 aC	0.3 ± 0.1 aB	0.7 ± 0.3abB
	Dec.	1.2 ± 0.4bC	1.4 ± 0.2cD	0.5 ± 0.1bC	0.0 ± 0.0aAB	0.2 ± 0.1 aB	0.6 ± 0.2bB
% WL	Feb.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0a	0.0 ± 0.0 aA	0.0 ± 0.0 aA
	Jun.	0.1 ± 0.0 aB	0.1 ± 0.0 aB	0.1 ± 0.0aAB	0.0 ± 0.0a	0.1 ± 0.0 aB	0.1 ± 0.0aAB
	Oct.	0.1 ± 0.0 aB	0.1 ± 0.0 aB	0.1 ± 0.0 aB	0.1 ± 0.0a	0.1 ± 0.0 aB	0.2 ± 0.1 aB
	Dec.	0.3 ± 0.2 cC	0.4 ± 0.1 dC	0.1 ± 0.0bcB	0.0 ± 0.0a	0.1 ± 0.4abAB	0.2 ± 0.0bcB
% DG	Feb.	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA	0.0 ± 0.0 aA
	Jun.	0.4 ± 0.1abC	0.4 ± 0.1abC	0.3 ± 0.0 aC	0.2 ± 0.0 aC	0.5 ± 0.1bD	0.6 ± 0.1bC
	Oct.	0.2 ± 0.0bcB	0.4 ± 0.1 dC	0.2 ± 0.0bcC	0.1 ± 0.0abB	0.3 ± 0.1 cC	0.0 ± 0.0 aA
	Dec.	0.1 ± 0.0bB	0.1 ± 0.0bB	0.1 ± 0.0abB	0.0 ± 0.0 aA	0.1 ± 0.0bB	0.2 ± 0.1bB
% GERM	Feb.	95.0 ± 0.9abA	97.3 ± 0.5bBC	95.1 ± 1.2 ab	96.8 ± 0.5 ab	92.4 ± 2.9 aA	95.3 ± 0.9abA
	Jun.	97.7 ± 0.4 aB	98.8 ± 0.3 aC	97.1 ± 0.6a	98.4 ± 0.3a	97.9 ± 0.3 aB	98.1 ± 0.4B
	Oct.	96.8 ± 0.5abAB	95.7 ± 0.5 aB	95.3 ± 1.0a	98.1 ± 0.5b	96.7 ± 0.7abB	96.3 ± 0.5 aA
	Dec.	96.7 ± 0.6bAB	88.1 ± 1.0 aA	96.3 ± 1.0b	98.4 ± 0.3b	97.1 ± 0.7bB	96.8 ± 0.6bAB
AFLA	Feb.	0.5 ± 0.3 aA	0.4 ± 0.2 aA	0.5 ± 0.3 aA	0.3 ± 0.3 aA	0.5 ± 0.2 aA	0.8 ± 0.3a
	Dec.	1.5 ± 0.1 aB	1.2 ± 0.1 aB	1.6 ± 0.2 aB	1.3 ± 0.1 aB	1.1 ± 0.2 aB	1.2 ± 0.0a

storage can result in low or no insect infestation for up to 3 months of storage. However, it is important to point out that most fumigations in Nigeria are inefficiently conducted and ineffective, leading to resurgence of insect populations right after treatments.

Psocids (total 3,614) and *S. zeamais* (total 1,255) were the most abundant types of insects found during the study. However, among all treatments, PICS was the most effective at mitigating population growth of all species of stored product insects encountered, and total numbers of psocids and *S. zeamais* found in PICS bags during the entire study were 0 and 8, respectively. *Sitophilus zeamais* was found in just one specific bag in Arisekola market. Data from this study clearly show that PICS bags were the most effective at keeping insects in check. According to Murdock and Baoua (2014), the safe, economical, insecticide-free method of storage represented by the PICS technology is now well established in West and Central Africa and can be used to store cowpea without losses to bruchids. Clearly the results of this study suggest that the PICS technology can also be used to store maize without losses to any of the stored product insect pests found in Nigeria. In fact, use of PICS technology for other commodities other than cowpea had been envisioned to lead to substantial increases in value of grain, reduce insecticide use, and increased food security across Africa and beyond (Murdock and Baoua, 2014).

Generally, populations of all insect pests found were higher in the Control during the October–December period. However, in the Control, *S. zeamais* populations were significantly higher than in other treatments in the October–December period. The high numbers of *S. zeamais* in the Control during the last 3 months of storage, but especially in December, most likely facilitated an increase in numbers of externally feeding insects. *Sitophilus zeamais* is an internal feeder that damages grain and makes it suitable for infestation by external feeders such as psocids, *O. surinamensis*, and *C. ferrugineus*. High numbers of *S. zeamais* in the Control highlights the need to use effective interventions to manage insect infestations in fumigated grain that is in long-term storage.

The Botanical treatment (*P. guineense*) did not offer good control of stored-product insect pests; future research should investigate applying this botanical at a higher dose rate. Additionally, in future tests, the *P. guineense* -treated grains could perhaps be placed in polythene-lined polypropylene bags to entrap the pungent insecticidal volatiles of *P. guineense* given that this botanical has fumigant properties (Nelson and Ntonifor, 2011). The highest numbers of *O. surinamensis* were found in the Botanical treatment in October and November and these densities were 4.0 and 8.4, respectively. The affinity of *O. surinamensis* for oil seeds may explain its greater abundance in the Botanical treatment (Haines, 1991). *P. guineense* contains fats and essential oils needed by insects (Nwankwo et al., 2014). The presence of relatively high levels of fats and essential oils in *P. guineense* needs to be factored into any consideration of its use for managing stored-product insect pests.

Raw DE used in this study was relatively effective against the beetle pests but not psocids. Although the DE treatment had a total of 33 *S. zeamais* during the entire period of the study, it had the highest number of psocids (total 1,449). Athanassiou et al. (2009a) also found that DEs when used alone will not provide effective control of psocids. The raw DE used in this study was obtained from Bularafa community in Yobe State, Northern Nigeria (Nwaubani et al., 2014). This raw DE has now been formulated into a commercial product called NSPRIDUST® which will be commercialized in Nigeria after product registration by National Agency for Food and Drug Administration and Control (NAFDAC) (G. Opit, personal communication). Diatomaceous earths (DEs), which are fossilized skeletal remains of diatoms (phytoplankton) which inhabited marine and fresh water bodies millions of years ago are promising alternatives to synthetic pesticides (Kavallieratos et al., 2005; Palyvos et al., 2006; Iatrou et al., 2010), such as permethrin used in this study. Diatomaceous earths are a good alternative for Nigerian smallholder farmers because they do not require specialized equipment or skills for application and have long-term efficacy, which arises from their high persistence (Athanassiou et al., 2005; Vayias et al., 2006). Moreover, the fact that NSPRIDUST is formulated from Nigeria-derived DE will probably make it affordable for Nigerian smallholder farmers and should facilitate increased adoption.

Just like in the case of DE, Permethrin was relatively effective against the beetles but not psocids. The limited effectiveness of pyrethroids against psocids is documented (Turner et al., 1991). For example, the psocid *Liposcelis bostrychophila* (Badonnel) has shown variable degrees of tolerance to contact pyrethroid insecticides, including permethrin, cypermethrin, and deltamethrin during laboratory evaluations (Turner et al., 1991). The fact that insecticides are relatively affordable and usually effective makes

Table 7
Correlation between total number of live insects, *Sitophilus zeamais*, *Prostephanus truncatus*, *Rhyzopertha dominica*, *Sitotroga cerealella*, *Cryptolestes ferrugineus*, *Tribolium castaneum*, *Oryzaephilus surinamensis*, and *Liposcelis* spp. in 700 g of sampled maize and the response variables percent insect damaged kernels by number (%IDKNB), percent weight loss (%WL), percent discolored kernels (%DG), temperature (TEMP), relative humidity (RH), and maize moisture content (MC). Correlation analyses were conducted using monthly mean values for the various variables. Mean values were used due to the large number of samples where no insects were detected.

Insect type(s)	Response variable	Pearson correlation coefficient (r)	*t*	*P*
Total live insects	%IDKNB	0.91	6.45	<0.01
	%WL	0.89	5.97	<0.01
	%DG	−0.08	−0.24	0.81
	TEMP	−0.24	−0.76	0.47
	RH	0.75	3.39	<0.01
	MC	0.77	3.6	0.01
S. zeamais	%IDKNB	0.79	3.84	<0.01
	WL	0.75	3.40	<0.01
	DG	−0.19	0.59	0.57
	TEMP	0.21	0.65	0.53
	RH	0.43	1.44	0.18
	MC	0.42	1.37	0.20
P. truncatus	%IDKNB	0.62	2.38	0.04
	%WL	0.63	2.24	0.04
	%DG	−0.21	0.66	0.52
	TEMP	0.24	0.73	0.49
	RH	0.28	0.00	0.41
	MC	0.26	0.81	0.44
C. ferrugineus	%IDKNB	0.88	5.54	<0.01
	%WL	0.86	5.13	<0.01
	%DG	−0.15	−0.47	0.65
	TEMP	0.04	0.12	0.91
	RH	0.58	2.12	0.06
	MC	0.58	2.11	0.06
T. castaneum	%IDKNB	0.73	3.20	0.01
	%WL	0.76	3.55	0.01
	%DG	0.00	0.00	0.99
	TEMP	−0.15	−0.46	0.66
	RH	0.55	1.16	0.08
	MC	0.54	1.91	0.08
O. surinamensis	%IDKNB	0.81	4.10	<0.01
	%WL	0.76	3.45	<0.01
	%DG	0.01	0.04	0.97
	TEMP	−0.26	−0.82	0.43
	RH	0.71	3.03	0.01
	MC	0.74	3.26	0.01
Liposcelis spp.	%IDKNB	0.59	2.18	0.06
	%WL	0.59	2.22	0.05
	%DG	0.06	0.18	0.86
	TEMP	−0.62	−2.37	0.04
	RH	0.73	3.16	0.01
	MC	0.78	3.71	<0.01

In all cases df = 1,9.

them the method of choice for insect pest control among most smallholder farmers throughout most of the developing world (Hell and Mutegi, 2011). However, chemical disinfestation has drawbacks such as the development of resistance, concerns about worker safety, consumer concerns regarding chemical residues in food, and other environmental-related concerns (Vadivambal et al., 2010).

ZeroFly bags were quite effective against beetle pests except in December when populations increased, but not substantially. Like in the case of DEs and Permethrin, ZeroFly bags were not effective against psocids. The individual yarns of the ZF bag fabric have deltamethrin incorporated in them and this insecticide is slowly released onto the surface of the yarn in a sustained manner (Vestergaard, 2014). As already stated above, psocids have shown tolerance to pyrethroids (Turner et al., 1991). Therefore, it is not surprising that ZeroFly bags, which rely on deltamethrin in the yarn to control insect infestation, were not effective against psocids. This study shows that psocids are difficult to control using standard control measures that are effective against other stored product pests. The difficulty controlling psocids using standard practices of protection and disinfestation is evident from other studies as well (Wang et al., 1999; Beckett and Morton, 2003; Athanassiou et al., 2009b; Huang et al., 2009). The fact that ZeroFly bags reduce infestation without direct application of insecticide to the maize makes them a much more preferable technology. Use of grain protectants such as permethrin can result in undesirable levels of insecticide residues in stored grain.

Temperature in the four storehouses where the study was conducted fluctuated during the 11 mo of maize storage but average temperatures were optimal for insect population growth. No correlation between temperature and insect numbers were found except in the case of psocids where there was a negative correlation ($r = -0.62$; $p = 0.04$). The correlation between psocid numbers and temperature may be due to the very small size of these insects ($\leq$1 mm), which makes their surface area to volume ratio high, and hence more susceptible to effects of temperature, especially temperature in the ranges observed in this study. The lack of correlation for other insect species was an expected result since temperatures throughout the study were within the ranges listed for optimum development of stored product insects (Howe,

1965; Fields, 1992). In studies conducted in Ghana, lack of correlation between insect numbers and temperature was also found (Danso et al., 2018; Manu et al., 2019).

Total number of live insects and numbers of *O. surinamensis* and psocids were each correlated with RH or MC. Danso et al. (2018) found no correlations between insect numbers and RH or MC. July–November is the rainy season. In this study, July is when most of the insects are first detected and their numbers generally increase thereafter in all treatments except PICS. Given that MC of maize was only 9.1% at the start of the study, increase in ambient RH at the onset of the rainy season would be expected to facilitate an increase in MC and to favour insect population growth. Psocid population levels were moderately high or high in all non-PICS treatments during the rainy months of July–November. This is probably because psocids thrive in high RH environments and in stored commodities with relatively high MC (Haines, 1991). Psocids are reported to thrive well at high relative humidities of 70–80%, and relative humidities below 60% are considered detrimental to their survival (Weng, 1986; Rees and Walker, 1990). High psocid numbers in Zerofly bags in July may be a result of psocids being tolerant or having resistance to deltamethrin (Ahmedani et al., 2010). Deltamethrin is incorporated in ZeroFly bags fabric at a concentration of 3,000 ppm (Vestergaard, 2014). From September to December, psocid population was significantly higher in DE than other treatments. The relatively higher abundance of psocids in the DE treatment may partly be due to the fact that DE when used alone is not effective against psocids (Athanassiou et al., 2009a). Globally psocids are now recognized as pests of substance (Phillips and Throne, 2010).

Total number of live insects and numbers of *S. zeamais*, *P. truncatus*, *C. ferrugineus*, *T. castaneum*, and *O. surinamensis* were each correlated with %IDKNB or %WL. The positive correlations between insect numbers and %IDKNB or %WL show how pest populations can reduce grain quality (Tefera et al., 2011). *Sitophilus zeamais* was the predominant internal feeder found. Therefore, *S. zeamais* most likely contributed to most of the kernel damage in this study. The activities of other internal feeders such as *P. truncatus, S. cerealella* and *R. dominica* may have contributed to kernel damage. This agrees with the findings of Tefera et al. (2011) who found that *P. truncatus* and *S. zeamais* adults caused significant grain damage over storage duration of 90 days. The percentage weight loss in the maize samples in this study was generally below estimated weight losses of 5–25% reported by researchers in Ghana (Ayertey, 1982; Anankware et al., 2013). A possible reason for the low %IDKNB and %WL found in this study is that well dried (9.1% MC), insect-free or near insect-free maize, was used to fill bags at the onset of storage hence markedly delaying insect infestation and damage. Insect numbers were not correlated with %DG in all cases. Germination was >92% in all treatments. In fact, in the PICS treatment, germination was 97–98% after 11 months of storage. Therefore, storage of sufficiently dried maize (9% MC) in hermetic bags for periods of up to 11 months is not detrimental to germination.

Aflatoxin is one of the most common and important mycotoxins found in maize (Suleiman et al., 2013). Aflatoxin levels in all treatments, at the start and end of the study, were below 20 ppb recommended by USFDA (USDA, 2015). The most likely reason for the low aflatoxin levels is that aflasafe was used in the production of the maize used for the present study, and the maize maintained its very low MC levels not favorable for growth of the aflatoxin producing fungus, *Aspergillus flavus*. Data from this study confirm that use of aflasafe keeps aflatoxin at safe levels in the field, and these levels can be kept low during storage, if low MC levels are maintained.

This study provides information on affordable and easy to use storage measures that can be easily adopted by low-resource and unskilled farmers, maize aggregators and other stakeholders in Nigeria, and other developing countries. Data from the present study show the PICS technology was the most effective at keeping insect infestations in check and preserving maize quality. Therefore, hermetic technologies such as PICS, ZeroFly® Hermetic bags, and GrainPro SuperGrainbags need to be more widely adopted for maize storage. Logistics of storing large quantities of maize in hermetic bags need to be investigated to ensure it is practical — affordable and convenient — for stakeholders. Diatomaceous earths are effective for insect pest control but need to be used in combination with other measures such as regular grain sampling and good sanitation, to ensure good efficacy. Non-hermetic ZeroFly bags should only be used to store well-dried and insect-free grain, and regular sampling of grain is recommended when these bags are being used. More research needs to be conducted on the use of *P. guineense* for stored product insect pest control.

Declaration of competing interest

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CRediT authorship contribution statement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jspr.2019.101566.

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