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Research article

Non-Chemical Preservation Methods for Stored Paddy Rice In Northern Nigeria

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Abstract
Effective reduced-risk storage technologies are now available for preservation of paddy rice. In an 18-month study, the effectiveness of six storage methods for controlling of insect pests and preservation of nutritional quality of paddy were evaluated. The preservation methods used were: ZeroFly® Combi bag, PICS bag, Polyethylene-Lined Polypropylene bag, NSPRIDUST® (diatomaceous earth-based product), Permethrin (Rambo™), and a polypropylene bag (Control). The study was conducted in storehouses located in two grain markets in North Central Nigeria: Ita-Amo market in Ilorin, Kwara State and Mokwa modern market in Mokwa, Niger State. Nine bags of 50 kg paddy rice were assigned to each treatment in each storehouse. Every six months, three bags from each treatment were destructively sampled and tested. Insect population levels were higher $P < 0.05$ in the Control (111.0±22.3) compared to other storage methods. The most common insect species observed were *Rhyzopertha dominica*, *Liposcelis* spp. and *Tribolium castaneum*. The Control had significantly higher IDK (0.8%) and WL (1.2%) compared to other treatments. The Combi, PICS, and NSPRIDUST treatments maintained 98% germination, while the Control had 22.1%. The mean aflatoxin levels in all treatments (2.1-3.8 ppb) were below the 20 ppb threshold. The data indicate that hermetic bags (PICS, ZeroFly® Combi and Polyethylene-Lined Polypropylene), NSPRIDUST and permethrin when used appropriately can effectively reduce quantitative losses and preserve the nutritional quality of paddy rice. The adoption of hermetic bags and DEs for paddy rice storage should be promoted to enhance rice availability and food security in developing countries.

Keywords: nutritional quality, postharvest loss, storage method, stored paddy rice

Introduction

The demand for rice (*Oryza* spp.) in several sub-Saharan Africa (SSA) countries is rapidly growing (Bin Rahman and Zhang, 2023). As a staple grain, rice is essential for food security and social stability due to its significance in diets, and its role in providing dietary calories more effectively than other cereals (Awika, 2011). Rice is a cash crop of significant economic importance in Nigeria and throughout Africa, produced mainly by smallholder farmers under rain-fed conditions (Oguntade *et al.*, 2014). Efforts to achieve rice sufficiency by 2030 are ongoing (Arouna *et al.*, 2021), but storage pests like the rice weevil, *Sitophilus oryzae* Linnaeus (Coleoptera: Curculionidae), lesser grain borer, *Rhyzopertha dominica* Fabricius (Coleoptera: Bostrichidae), Angoumois grain moth *Sitotroga cerealella* Olivier (Lepidoptera: Gelechiidae), red flour beetle, *Tribolium castaneum* Herbst (Coleoptera: Tenebrionidae), and *Liposcelis* spp. (Psocoptera: Liposcelididae) damage stored paddy, causing reduction in quality and quantity (Togola *et al.*, 2013). Though, paddy husk offers some protection from infestation, varietal type may confer susceptibility/resistance against stored-insect pests (Ajao *et al.*, 2019). Grain storage losses, mainly due to insect infestation, range between 10-20% for stored commodities in developing countries (Kumar and Kalita, 2017). Without intervention, paddy rice losses range from 2.8% to 21.8% (Stathers *et al*., 2020) and when traditional polypropylene bags were used, losses ranged from 3% to 8.7% over 7-18 months (Baoua *et al*., 2016). Farmers often sell grains immediately after harvest or use synthetic insecticides, which are costly, sometimes ineffective, and pose health and environmental risks (Okori *et al*., 2022). In addition, climate change presents new challenges for grain storage by altering pest behaviour and insecticide effectiveness (Sharma and Prabhakar, 2014). Environmentally friendly and sustainable storage technologies are gaining attention as part of Integrated Pest Management (IPM) programs. In Nigeria, over 75% of farming households use woven polypropylene bags, despite their ineffectiveness against insects and other storage pests (Abdoulaye *et al*., 2016). Therefore, this study evaluated reduced-risk technologies such as NSPRIDUST® (hereafter referred to as DE), Purdue Improved Crop Storage (PICS) bags, ZeroFly® Combi Hermetic (CZFH) bags, Polyethylene-Lined Polypropylene Hermetic (PPPH) bags, and Permethrin (Rambo® Insect Powder, PERM) for preserving paddy rice. Traditional polypropylene (PP) bags were used as the Control.

NSPRIDUST® is a diatomaceous earth product developed by the Nigerian Stored Products Research Institute, offering low mammalian toxicity, affordability, and ease of application (Nwaubani *et al*., 2020). PICS bags use triple-layer hermetic technology to create a hypoxic environment that inhibits pests (Baributsa and Ignacio, 2020). The CZFH bag is a laminated deltamethrin-insecticide incorporated bag, produced by the Nigerian Bag Manufacturing Company (BAGCO) for Vestergaard SA, which innovates on existing ZeroFly® ordinary and double-layer hermetic bag designs for improved grain storage. PPPH bags combine a polypropylene bag with an inner polyethylene liner of 80 µm thickness for enhanced protection.

Studies have shown varying degrees of efficacy for these reduced-risk methods in SSA (Nwaubani *et al*., 2020; Opoku *et al*., 2023b), but data on their effectiveness for paddy rice storage in North-Central Nigeria is limited. This study aimed to evaluate these technologies for quality preservation of paddy rice stored in grain markets in North-Central Nigeria in order to support intensified rice production efforts in SSA and enhance food and nutrition security.

Materials and Methods

Source of paddy rice and study sites

The study used the 'FARO 44' rice variety which was purchased from a farm in Majin Gari village, Niger state, and then transported to the grain markets. The study took place in two North-Central Nigerian markets from February 2020 to July 2021. It involved three storehouses in two grain markets: Mokwa modern market in Mokwa, Niger State (9°29'28" N 5°05'47" E) and Ita-Amo market in Ilorin, Kwara State (8°29'34.8" N 4°32'59.9" E). Mokwa had two storehouses, located about 10 m apart while Ilorin had one storehouse. The markets are ~122 km apart. These locations were chosen to simulate typical grain storage conditions and due to the likelihood of high infestation pressure from nearby non-study storehouses.

Storage treatments and experimental design

Six storage methods compared were: DE, CZFH (single-layer hermetic bag), PPPH (double-layer hermetic bag), PICS (triple-layer hermetic bag), PERM, and Control (PP bag). Paddy rice was stored in specialised hermetic bags (PICS, CZFH, and PPPH), mixed with a protectant (DE or PERM) in polypropylene (PP) bags, and as untreated in PP bags (Control). Detailed information on hermetic bag set up (used) and admixing procedures have been reported (Nwaubani *et al*., 2020). In each storehouse, nine 50 kg bags were assigned to each treatment, arranged on separate pallets to prevent moisture absorption from the floor, with pallets placed one meter apart. Each storehouse contained 54 bags. Temperature and relative humidity data loggers (HOBO U12, Onset Computer Corporation, Bourne, MA, USA) were installed inside and outside each storehouse to record environmental conditions hourly. The study used a randomized complete block design (RCBD) with six treatments. Each treatment was replicated three times, that is, each storehouse was a replicate. At each sampling event, 3 bags per treatment in each storehouse were sampled, that is, a sub-replication of three.

Sampling and data collection

A 1.2 meter open ended grain trier (Seedburo® Equipment Company, IL, USA) was used to collect paddy rice samples from bags. Three samples, each ~350 g were taken from each bag (one from the middle and two from the sides) and placed in a 3-litre Ziploc bag. The trier was inserted into the bag while closed, opened to collect the sample, then closed and removed. For non-hermetic treatments (DE, PERM and Control), a 3-cm opening was made at the seam of each bag to facilitate sampling and was sealed with duct tape afterwards. Samples were taken from three randomly selected bags from each of the six treatments, with destructive sampling occurring every six months. Destructive sampling as described in this study means the required samples in each treatment were taken from three randomly selected bags during each sampling event, and these bags were then discontinued from the study.

Extraction of insects from samples

Recovery of insects to estimate insect pest infestation based on presence and types of insects was conducted using U.S. Standard sieve #8 (2.36 mm openings) (Seedburo® Equipment Company, IL, USA) to sift 1-kg lots of samples from each bag that had been collected. More details on the recovery method used are described by Nwaubani *et al*. (2020) and insect species were identified, and the numbers of each species recorded.

Grain quality variables

To estimate percentage insect-damaged kernels by number (%IDKn) and weight loss (%WL), 125-g sub-samples from the 1-kg lot samples collected from each bag were used. This modification of the 250-g sub-sample (Nwaubani *et al*., 2020) was used because 125-g sub-samples contained more manageable numbers of paddy rice kernels to process (count). However, %IDKn, %WL and %GERM were all estimated using standard procedures which have been previously described by Nwaubani *et al*., (2020).

Aflatoxin

Five-gram samples were taken from the 1-kg samples previously described to estimate aflatoxin levels using VICAM AflaV™ test kit, following the manufacturer's specifications. The test involved sample grinding, extraction, solute preparation and test procedures and was conducted according to manufacturer's instructions (https://www.vicam.com/store/afla-v-instruction-guide) (Accessed on 3 August, 2024).

Proximate composition analysis

To evaluate the effect of storage methods (treatments) on the nutritional quality of the paddy rice over 18 months of storage, all components of proximate composition (moisture, crude fibre, protein, fat and ash) were determined using standard analytical methods (AOAC, 2005) and as described in Otitodun *et al*. (2021).

Data analyses

Statistical analyses were performed with SAS Version 9.4 (SAS Institute, Cary, NC). Effects of sampling date/month and type of stored grain protection method (Treatment) were evaluated using analysis of variance (ANOVA), with market storehouse as the blocking factor (PROC MIXED). For the analysis of live insect counts, a square root transformation was applied when necessary, but untransformed values are reported. The simple effects of type of treatment at a given date were assessed using protected planned contrasts (SLICE option in an LSMEANS statement), and the same option was used to assess the simple effects of date within a given treatment. For response variables expressed as percentages, data analyses used an arcsine square root transformation to stabilize variances, but untransformed percentages are reported.

Results

Temperature and relative humidity

Storehouse temperature in three replicates during the 18 months of the experiment was 24.3–32.6, 24.6–32.8, and 24.8–31.5°C, respectively. These corresponded to the means of 28.5, 28.7 and 28.2°C, respectively. For relative humidity (r.h.), values were 54.5–73.8, 53.6–74.5, and 51.9–74.3%, respectively. These corresponded to the means of 64.2, 64.1 and 63.1%, respectively.

Insect infestation

The primary insect pests found in paddy samples during the study were *R. dominica* and *S. oryzae*, whereas the secondary insect pests found were *T. castaneum*, *Cryptolestes ferrugineus* Stephens (Coleoptera: Laemophloeidae), *Oryzaephilus surinamensis* Linnaeus (Coleoptera: Silvanidae) and *Liposcelis* spp. (hereafter referred to as psocids). For live *R. dominica* and psocids, the main effect sampling date, treatments and their interaction were significant but not the interaction for *T. castaneum*. However, for *S. oryzae, C. ferrugineus*, and *O. surinamensis,* main effect sampling date, treatments and interaction were not significant (Table 1). Initially absent, *R. dominica* increased significantly after 6 months (July 2020) and consistently until July 2021. In July 2020, the Control (55.1) and PERM (9.0) had higher insect densities (individuals/kg) compared to DE (0.2), PICS (0.1), PPPH (0.8), and CZFH (0.7). By July 2021, densities were highest in the Control (88.1) and PERM (15.8), while DE, PPPH, and CZFH had densities of 4.1, 6.8, and 7.0, respectively, and PICS had a density of 0.5 (Table 2).

Table 1: ANOVA results for numbers of six stored-product insect species in paddy rice stored with different treatments (TRT) and sampling dates (SD)

Insect species	Source	F	*P*
R. dominica			
	SD	72.4	<0.0001
	TRT	106.1	<0.0001
	SD*TRT	12.33	<0.0001
S. oryzae			
	SD	1.00	0.4010
	TRT	1.00	0.4280
	SD*TRT	1.00	0.4707
T. castaneum			
	SD	7.28	0.0004
	TRT	8.76	<0.0001
	SD*TRT	1.20	0.3017
C. ferrugineus			
	SD	1.44	0.2430
	TRT	1.24	0.3070
	SD*TRT	0.53	0.9123
O. surinamensis			
	SD	1.41	0.2510
	TRT	1.27	0.2933
	SD*TRT	1.83	0.0575
Psocids			
	SD	39.56	<0.0001
	TRT	42.73	<0.0001
	SD*TRT	5.51	<0.0001

In all cases, degrees of freedom (df) for treatment, sampling, and treatment and sampling date interaction are 5, 48; 3, 48; and 15, 48, respectively.

Regarding *S. oryzae*, the weevil was only detected in the Control (1.2) in February 2021 and was absent in all other treatments (Table 2). No live *T. castaneum* was found at the start of storage in February 2020. Throughout storage, densities were less than 1 in all treatments except CZFH and the Control. In the Control, densities were 8.8 in July 2020 and 8.5 in July 2021; in the CZFH bag, densities were 2.1 and 1.5, respectively, for the same months. In the case of *C. ferrugineus*, it was first found in July 2020 in the Control (0.2), PPPH (0.3), and CZFH (0.1) treatments. By July 2021, only DE (0.1) and PPPH (0.1) had *C. ferrugineus* (Table 2).

For *O. surinamensis*, the insect was first found in February 2021 only in the PPPH treatment (1.1). By July 2021, it was found only in the PERM (1.6) and Control (0.1) treatments. Regarding psocids, they were more abundant in the Control (7.8) compared to PERM (1.6) and DE (1.0) in July 2020. Psocids were absent in CZFH, PICS, and PPPH treatments in February 2021. By July 2021, all treatments had psocids, with the highest numbers in the Control (14.3) and the lowest in PICS (0.1).

Table 2: Mean (±SE) number of six stored-product insect species in stored paddy rice during sampling months of February 2020 and July 2021.

Species	TRT	Feb 2020	Jul 2020	Feb 2021	Jul 2021

R. dominica	CON	0.0 ± 0.0^{A}	55.1 ± 7.9^{cB}	65.4 ± 16.6^{cB}	88.1 ± 14.9^{dC}
	DE	0.0 ± 0.0^{A}	0.2 ± 0.1^{aA}	0.9 ± 0.4^{aA}	4.1 ± 0.1^{bB}
	PICS	0.0 ± 0.0	0.1 ± 0.1^{a}	1.1 ± 1.1^{a}	0.5 ± 0.2^{a}
	PPPH	0.0 ± 0.0^{A}	0.8 ± 0.2^{aA}	0.8 ± 0.2^{aA}	6.8 ± 0.5^{bB}
	PERM	0.0 ± 0.0^{A}	9.0 ± 2.3^{bB}	9.0 ± 2.3^{bB}	15.8 ± 7.1^{cB}
	CZFH	0.0 ± 0.0^{A}	0.7 ± 0.0^{aA}	1.5 ± 0.8^{aA}	7.0 ± 1.3^{bcB}
S. oryzae	CON	0.0 ± 0.0^{A}	0.0 ± 0.0^{A}	1.2 ± 1.2^{B}	0.0 ± 0.0^{A}
	DE	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	PICS	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	PPPH	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	PERM	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	CZFH	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
T. castaneum	CON	0.0 ± 0.0^{A}	8.8 ± 5.7^{bB}	8.8 ± 5.7^{bB}	8.5 ± 6.8^{bB}
	DE	0.0 ± 0.0	0.2 ± 0.1^{a}	0.2 ± 0.1^{a}	0.6 ± 0.1^{a}
	PICS	0.0 ± 0.0	0.6 ± 0.6^{a}	0.2 ± 0.2^{a}	0.7 ± 0.4^{a}
	PPPH	0.0 ± 0.0	0.8 ± 0.5^{a}	0.8 ± 0.5^{a}	0.2 ± 0.1^{a}
	PERM	0.0 ± 0.0	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}	0.6 ± 0.3^{a}
	CZFH	0.0 ± 0.0^{A}	2.1 ± 1.0^{abB}	2.0 ± 1.1^{aB}	1.5 ± 0.4^{aAB}
C. ferrugineus	CON	0.0 ± 0.0	0.2 ± 0.2^{ab}	0.0 ± 0.0	0.0 ± 0.0
	DE	0.0 ± 0.0	0.0 ± 0.0^{a}	0.0 ± 0.0	0.1 ± 0.1
	PICS	0.0 ± 0.0	0.0 ± 0.0^{a}	0.0 ± 0.0	0.0 ± 0.0
	PPPH	0.0 ± 0.0^{A}	0.3 ± 0.3^{bB}	0.1 ± 0.1^{AB}	0.1 ± 0.1^{AB}
	PERM	0.0 ± 0.0	0.0 ± 0.0^{a}	0.0 ± 0.0	0.0 ± 0.0
	CZFH	0.0 ± 0.0	0.1 ± 0.1^{ab}	0.0 ± 0.0	0.0 ± 0.0
O. surinamensis	CON	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0^{a}	0.1 ± 0.1^{a}
	DE	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}
	PICS	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}
	PPPH	0.0 ± 0.0^{A}	0.0 ± 0.0^{A}	1.1 ± 0.6^{bB}	0.0 ± 0.0^{aA}
	PERM	0.0 ± 0.0^{A}	0.0 ± 0.0^{A}	0.0 ± 0.0^{aA}	1.6 ± 1.6^{bB}
	CZFH	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}
Psocids	CON	0.0 ± 0.0^{A}	7.8 ± 0.4^{cB}	5.6 ± 0.4^{cB}	14.3 ± 0.5^{cC}
	DE	0.0 ± 0.0^{A}	1.0 ± 0.9^{bB}	1.7 ± 1.5^{bBC}	2.3 ± 0.5^{bC}
	PICS	0.0 ± 0.0	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}	0.1 ± 0.1^{a}
	PPPH	0.0 ± 0.0^{A}	0.0 ± 0.0^{aA}	0.0 ± 0.0^{aA}	1.4 ± 0.9^{bB}
	PERM	0.0 ± 0.0^{A}	1.6 ± 0.3^{bB}	0.6 ± 0.3^{bAB}	4.8 ± 2.1^{bC}
	CZFH	0.0 ± 0.0^{A}	0.0 ± 0.0^{aA}	0.0 ± 0.0^{aA}	1.0 ± 0.5^{abB}

Treatments: Control (CON), NSPRIDUST® (DE), PICS hermetic bags (PICS), Polyethylene-Lined Polypropylene hermetic bags (PPPH), Rambo (PERM), and Combi ZeroFly® Hermetic bags (CZFH). Significant differences between treatments for each sampling month are denoted with different lower-case letters and differences among sampling month for each treatment are denoted by different upper-case letters. If there are no lower-case or upper-case letters, there are no significant differences ($P > 0.05$).

Percent IDK and WL

The main effects of sampling date, treatment, and their interaction were significant for both %IDKn and %WL (Tables 3). Except for Permethrin and Control, all treatments showed no insect-damaged kernels (0.0%) throughout storage. In the Control, %IDKn increased from 0.4% to 0.8% in the last six months. Weight loss (%WL) was also significant, with the Control having a range from 0.3% to 1.2%. Permethrin treatment showed only a slight increase in damage and weight loss (0.1%) in the final month, while other treatments had no weight loss during the entire period (Table 4).

Germination

For %GERM, the main effect sampling date and treatment and their interaction were significant (Table 3). Initially, the mean germination rate was 98.3%. Significant differences emerged by July 2020, with the Control treatment showing lower germination (66.0%). By July 2021, hermetic bags (PICS, PPPH, and CZFH) and DE treatment maintained germination rates ≥ 98%, while PERM had 91.5%, and the Control had 22.1% (Table 4). The Control treatment showed a 76.2% reduction in germination after 18 months, whereas other storage methods maintained high germination levels.

Aflatoxin

The study found that aflatoxin levels were significantly affected by both the sampling date and treatment, as well as their interaction (Table 3). In the PERM treatment, aflatoxin levels remain constant at 2.8 ppb from the start and end of the study, whereas the levels decreased in PICS, DE, CZFH and PPPH bags by the end of the study in July 2021 (Table 4). However, in the Control, aflatoxin levels increased to were 3.8 ppb.

Table 3: ANOVA results for quality variables of paddy rice stored with different treatments (TRT) and sampling dates (SD)

Variable	Source	*F*	*P*
% IDK	SD	23.19	<0.0001
	TRT	52.74	<0.0001
	SD*TRT	6.59	<0.0001
% WL	SD	41.50	<0.0001
	TRT	120.12	<0.0001
	SD*TRT	18.11	<0.0001
% GERM	SD	71.27	<0.0001
	TRT	213.68	<0.0001
	SD*TRT	33.03	<0.0001
AFLA	SD	50.35	<0.0001
	TRT	95.12	<0.0001
	SD*TRT	15.35	<0.0001

Quality variables: Percentage number of insect-damaged kernel (%IDKn), percentage weight loss (%WL), percentage germination (%GERM) and aflatoxin level (Afla). In all cases, degrees of freedom (df) for treatment, sampling, and treatment and sampling date interaction are 5, 48; 3, 48; and 15, 48, respectively.

Nutritional composition

For all the nutrient quality variables of paddy rice analysed, the main effect sampling date was significant, but treatment and treatment-sampling date interaction were not significant (Table 5). In general, there was reduction in the nutrient quality variables found in all the treatments except for percentage moisture content and fibre after 18 months of storage. For moisture content, values significantly increased from 8.9±0.0% to 14.3±0.2% whereas in the case of fibre content, the value (1.8±0.2) did not differ from the initial values obtained in PICS, PPPH, PERM and CZFH; on the whole most fibre content values were not different.

Table 4: Mean (±SE) quality variables of paddy rice stored from February 2020 to July 2021.

Variables	TRT	Feb 2020	Jul 2020	Feb 2021	Jul 2021
% IDK	CON	$0.0±0.0^{A}$	$0.4±0.0^{bB}$	$0.4±0.1^{bB}$	$0.8±0.3^{cC}$
	DE	0.0±0.0	$0.0±0.0^{a}$	$0.0±0.0^{a}$	$0.0±0.0^{a}$
	PICS	0.0±0.0	$0.0±0.0^{a}$	$0.0±0.0^{a}$	$0.0±0.0^{a}$
	PPPH	0.0±0.0	$0.0±0.0^{a}$	$0.0±0.0^{a}$	$0.0±0.0^{a}$
	PERM	$0.0±0.0^{A}$	$0.0±0.0^{aA}$	$0.0±0.0^{aA}$	$0.1±0.0^{bB}$
	CZFH	0.0±0.0	$0.0±0.0^{a}$	$0.0±0.0^{a}$	$0.0±0.0^{a}$
% WL	CON	$0.0±0.0^{A}$	$0.3±0.1^{bB}$	$0.5±0.0^{bC}$	$1.2±0.2^{cD}$
	DE	0.0±0.0	$0.0±0.0^{a}$	$0.0±0.0^{a}$	$0.0±0.0^{a}$
	PICS	0.0±0.0	$0.0±0.0^{a}$	$0.0±0.0^{a}$	$0.0±0.0^{a}$
	PPPH	0.0±0.0	$0.0±0.0^{a}$	$0.0±0.0^{a}$	$0.0±0.0^{a}$
	PERM	$0.0±0.0^{A}$	$0.0±0.0^{aA}$	$0.0±0.0^{aA}$	$0.1±0.0^{bB}$
	CZFH	0.0±0.0	$0.0±0.0^{a}$	$0.0±0.0^{a}$	$0.0±0.0^{a}$
% GERM	CON	$98.3±0.0^{D}$	$66.0±2.8^{aC}$	$46.6±0.7^{aB}$	$22.1±2.5^{aA}$
	DE	$98.3±0.0^{B}$	$97.9±0.5^{bAB}$	$95.2±0.6^{cA}$	$98.1±0.3^{cAB}$
	PICS	98.3±0.0	$97.7±0.1^{b}$	$96.3±1.2^{c}$	$98.7±0.5^{c}$
	PPPH	$98.3±0.0^{B}$	$97.1±0.2^{bB}$	$93.9±2.1^{cA}$	$97.9±1.0^{cB}$
	PERM	$98.3±0.0^{B}$	$96.7±1.1^{bB}$	$85.7±5.2^{bA}$	$91.5±0.3^{bA}$
	CZFH	$98.3±0.0^{B}$	$97.0±0.5^{bAB}$	$95.1±2.2^{cA}$	$98.0±0.2^{cA}$
AFLA	CON	$2.8±0.0^{A}$	$3.2±0.1^{cB}$	$3.2±0.1^{cB}$	$3.8±0.2^{cC}$
	DE	$2.8±0.0^{B}$	$2.0±0.1^{aA}$	$1.9±0.1^{aA}$	$2.2±0.1^{aA}$
	PICS	$2.8±0.0^{B}$	$2.0±0.1^{aA}$	$2.0±0.0^{aA}$	$2.1±0.1^{aA}$
	PPPH	$2.8±0.0^{B}$	$2.7±0.1^{bB}$	$2.0±0.0^{aA}$	$2.2±0.1^{aA}$
	PERM	$2.8±0.0^{B}$	$2.3±0.0^{bA}$	$2.4±0.0^{bA}$	$2.8±0.0^{bB}$
	CZFH	$2.8±0.0^{B}$	$2.2±0.0^{aA}$	$2.1±0.0^{aA}$	$2.3±0.1^{aA}$

Treatments: Control (CON), NSPRIDUST® (DE), PICS hermetic bags (PICS), Polyethylene-Lined Polypropylene hermetic bags (PPPH), Rambo (PERM), and Combi ZeroFly® Hermetic bags (CZFH). Significant differences between treatments for each sampling month are denoted with different lower-case letters and differences among sampling month for each treatment are denoted by different upper-case letters. If there are no lower-case or upper-case letters, there are no significant differences ($P > 0.05$).

Table 5: ANOVA results for nutritional composition of paddy rice stored with different treatments (TRT) and sampling dates (SD)

Variable	Source	F	*P*
Ash content	SD	43.91	<0.0001
	TRT	2.09	0.0828
	SD*TRT	1.10	0.3827
Carbohydrate content	SD	128.22	<0.0001
	TRT	0.71	0.6163
	SD*TRT	0.47	0.9463
Fat content	SD	87.61	<0.0001
	TRT	0.74	0.5973
	SD*TRT	0.49	0.9319
Fibre content	SD	4.37	0.0085
	TRT	0.55	0.7352
	SD*TRT	0.42	0.9661
Moisture content	SD	494.70	<0.0001
	TRT	1.09	0.3758
	SD*TRT	0.58	0.8779
Protein content	SD	21.36	<0.0001
	TRT	0.75	0.5887
	SD*TRT	0.71	0.7596

In all cases, degrees of freedom (df) for treatment, sampling, and treatment and sampling date interaction are 5, 48; 3, 48; and 15, 48, respectively.

Table 6: Mean (±SE) percentage nutritional composition of stored paddy rice during sampling months of February 2020 to July 2021**.**

Variables	TRT	Feb 2020	Jul 2020	Feb 2021	Jul 2021
%Ash	CON	1.7±0.0^{B}	1.6±0.0^{AB}	1.4±0.1^{abA}	1.6±0.2^{bAB}
	DE	1.7±0.0^{B}	1.6±0.1^{B}	1.3±0.1^{aA}	1.4±0.1^{aA}
	PICS	1.7±0.0^{C}	1.6±0.0^{B}	1.3±0.0^{abA}	1.4±0.0^{aAB}
	PPPH	1.7±0.0^{B}	1.7±0.1^{B}	1.3±0.0^{abA}	1.4±0.0^{aA}
	PERM	1.7±0.0^{B}	1.6±0.0^{B}	1.5±0.1^{bA}	1.5±0.0^{bA}
	CZFH	1.7±0.0^{B}	1.6±0.0^{B}	1.4±0.1^{aA}	1.4±0.0^{aA}
%CHO	CON	79.5±0.0^{C}	77.0±0.1^{B}	76.2±0.6^{AB}	75.2±0.5^{A}
	DE	79.5±0.0^{C}	76.9±0.5^{B}	76.1±0.2^{AB}	75.2±0.2^{A}
	PICS	79.5±0.0^{C}	77.3±0.3^{B}	75.5±0.7^{A}	75.8±0.7^{A}
	PPPH	79.5±0.0^{C}	76.9±0.5^{B}	76.4±0.2^{AB}	75.4±0.8^{A}
	PERM	79.5±0.0^{C}	76.7±0.3^{B}	75.3±0.8^{A}	74.9±0.3^{A}
	CZFH	79.5±0.0^{C}	77.3±0.5^{B}	76.2±0.2^{A}	75.3±0.1^{A}
%Fat	CON	1.4±0.0^{C}	0.9±0.0^{A}	0.9±0.1^{A}	1.2±0.1^{abB}
	DE	1.4±0.0^{C}	0.9±0.0^{A}	0.9±0.1^{A}	1.2±0.1^{abB}
	PICS	1.4±0.0^{B}	0.9±0.1^{A}	0.9±0.1^{A}	1.3±0.0^{abB}
	PPPH	1.4±0.0^{C}	0.9±0.0^{A}	1.0±0.1^{B}	1.2±0.1^{abB}
	PERM	1.4±0.0^{C}	0.9±0.0^{A}	1.0±0.1^{B}	1.3±0.1^{bC}
	CZFH	1.4±0.0^{C}	0.9±0.0^{A}	1.0±0.1^{AB}	1.1±0.1^{aB}
%Fibre	CON	1.9±0.0^{B}	1.8±0.0^{AB}	1.8±0.1^{AB}	1.6±0.2^{A}
	DE	1.9±0.0^{B}	1.8±0.1^{AB}	1.9±0.0^{B}	1.5±0.1^{A}
	PICS	1.9±0.0	1.8±0.1	1.8±0.1	1.8±0.1
	PPPH	1.9±0.0	1.8±0.1	2.0±0.0	1.8±0.2
	PERM	1.9±0.0	1.8±0.0	1.8±0.2	1.6±0.1
	CZFH	1.9±0.0	1.8±0.1	1.8±0.2	1.8±0.1
%Moisture	CON	8.9±0.0^{A}	11.6±0.1^{B}	13.1±0.2^{C}	13.9±0.3^{abD}
	DE	8.9±0.0^{A}	11.7±0.1^{B}	13.4±0.1^{C}	14.0±0.1^{abC}
	PICS	8.9±0.0^{A}	11.7±0.1^{B}	13.7±0.2^{C}	13.4±0.4^{aC}
	PPPH	8.9±0.0^{A}	11.5±0.8^{B}	13.3±0.1^{C}	14.0±0.3^{abC}
	PERM	8.9±0.0^{A}	11.8±0.2^{B}	13.8±0.4^{C}	14.3±0.2^{bC}
	CZFH	8.9±0.0^{A}	11.3±0.5^{B}	13.4±0.3^{C}	14.0±0.4^{abC}
%Protein	CON	7.0±0.0^{AC}	7.2±0.1^{C}	6.4±0.4^{abAB}	6.4±0.3^{B}
	DE	7.0±0.0^{B}	7.2±0.2^{B}	6.3±0.2^{abA}	6.7±0.2^{AB}
	PICS	7.0±0.0^{B}	7.3±0.2^{B}	6.9±0.4^{bAB}	6.4±0.3^{A}
	PPPH	7.0±0.0^{B}	7.2±0.0^{B}	6.0±0.2^{aA}	6.3±0.3^{A}
	PERM	7.0±0.0^{B}	7.2±0.2^{B}	6.7±0.4^{bAB}	6.4±0.2^{A}
	CZFH	7.0±0.0^{B}	7.1±0.1^{B}	6.3±0.1^{abA}	6.5±0.2^{A}

Treatments: Control (CON), NSPRIDUST® (DE), PICS hermetic bags (PICS), Polyethylene-Lined Polypropylene hermetic bags (PPPH), Rambo (PERM), and Combi ZeroFly® Hermetic bags (CZFH). Significant differences between treatments for each sampling month are denoted with different lower-case letters and differences among sampling month for each treatment are denoted by different upper-case letters. If there are no lower-case or upper-case letters, there are no significant differences ($P > 0.05$).

Discussion

The study identified six insect species of stored paddy rice: *R. dominica*, *Liposcelis* spp., *T. castaneum*, *S. oryzae*, *C. ferrugineus*, and *O. surinamensis*, with the first three being the most prevalent. The Control (PP bags) recorded the highest number of live insects of the different species than any other treatment throughout the duration of the study. The high insect abundance in the Control may be related to the porous fabric of the PP bag which permits the release of volatile substances from stored rice to the external environment, and thereby attracting insects. In this case, *R. dominica* numbers increased over time, leading to increased abundance of external feeders such as *T. castaneum* and psocids. Despite the fact that these external feeders are known to feed on damaged grains, they can attack intact kernels as well (Gautam *et al*., 2013). In contrast, the hermetic bags (PICS, PPPH, and CZFH) and DE treatment were most effective in preserving rice, with significantly fewer insects. The greater effectiveness of hermetic technologies observed in this study is probably a result of the depletion of oxygen and accumulation of carbon dioxide in the internal atmosphere inside bags due to the metabolic activities of both grain and insects during the storage period (Odjo *et al*., 2022). The DE used provided good protection against insect pests. After 18 months, only 69 *R. dominica* and 45 psocids were found in DE-treated rice. However, the efficacy of DE decreased over time, which may be due to the physical and chemical properties of paddy rice (Chanbang *et al*., 2007). DE kills insects by causing water loss through desiccation (Korunic, 1998). Its local availability, ease of application, and cost-effectiveness make it a more viable alternative to chemical controls like permethrin. However, data from this study show that paddy rice treated with DE should probably not be stored for more than 1 year. The efficacy of permethrin against *R. dominica* also decreased by the end of the storage period. While PERM showed higher persistence on stored maize in previous studies (Nwaubani *et al*., 2020), it generally has low persistence, often lasting only 6 months (Mlambo *et al*., 2018).

Ambient conditions of temperature range between 28.2 – 28.7°C and relative humidity range of 63.1 – 64.2% in the storehouses were conducive for pest development hence influenced insect populations favourably. These values have been reported to be within optimum development values for *R. dominica* and also secondary pests of stored paddy rice (Rajendran, 2020).

The higher IDK and WL values found in the Control compared to other storage methods, corroborates previous studies that found PP bags are inadequate for protecting stored paddy rice from insect pests (Covele *et al*., 2020). Grain damage affects quality, reducing food grade and palatability, and in paddy rice, it lowers milling yield and the proportion of whole kernels (Arthur *et al*., 2012). Despite the hermetic bags having some infestation, kernel damage was negligible. This is corroborated by Baributsa and Ignacio (2020), who opined similar efficacy among different hermetic bags irrespective of their composition. Hermetic bags have been reported to effectively preserve grain and seed quality for over 6–18 months (Mutambuki and Likhayo, 2021), while PP bags without pesticide treatment are effective for only up to a few months (Nwaubani *et al*., 2020). Storage losses in this study were lower than those previously reported which were in the range of 3 – 8.7% (Baoua *et al*., 2016).

Maintaining good viability for planting is essential, but storage significantly affects this viability. The differences in germination rates observed in this study are likely due to variations in insect infestation and the physical condition of paddy kernels. The Control had the highest pest levels, which can damage the nutrient-rich parts of the seeds, including the embryo, leading to reduced germination (Kuyu *et al.*, 2022). Seeds stored in non-hermetic containers are subject to environmental changes, while hermetic storage maintains more stable conditions and preserves germination potential (Villers, 2017). Seeds intended for planting should have at least an 85% germination rate after 12 months of storage (Fufa *et al*., 2020). Given that many Nigerian farmers rely on saved seeds, this study suggests that storing paddy in PICS, PPPH, and CZFH hermetic bags or treating with DE can achieve reasonable germination rates.

Aflatoxin, a toxic product of fungal infections, contaminates cereals like rice. In this study, aflatoxin levels remained controlled in all treatments except the Control, where there was a significant increase during storage. This increase was likely due to high insect infestation and elevated IDK (Sinha and Sinha, 1991), and fungal infection (Opoku *et al*., 2023a). Despite this, aflatoxin levels were below the international 10 – 20 ppb limit (PACA, 2021).

The nutritional quality of stored grain is affected by insect pests and rodents due to their feeding activities (FAO, 2011). Storage pests cause significant qualitative losses, and eventually cause reduction in nutritional quality. Therefore, storage pests contributed to the observed significant reduction in nutrient quality of paddy in the Control and other treatments. The decrease in the nutrient content may possibly be related to insect activity and damage recorded on paddy. Insects (internal and external feeders) are known to feed on the nutrient dense portion of grains especially fat (Keskin and Ozkaya, 2015). The moisture content increased in all treatments during storage with PICS having the lowest MC after 18 months. The observed increase in MC could be a result of insect infestation within the paddy mass. The MC of stored paddy rice in this study falls within the 8.9-14.1% range reported by Baoua *et al*. (2016).

Conclusion

This study highlights the effectiveness of non-chemical storage methods for paddy rice using hermetic storage bags and diatomaceous earth (DE). All hermetic bags tested, including PICS, ZeroFly hermetic Combi, and Polyethylene-Lined Polypropylene hermetic bags, provided effective storage and are recommended for low-resource and medium-scale farmers to extend the shelf-life of stored paddy rice. NSPRIDUST diatomaceous earth is also recommended as a non-toxic, locally available protectant — these attributes ensure its long-term sustainability. However, paddy rice treated with NSPRIDUST should not be stored for more than one year.

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Conflicts of Interest

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