Influence of Grain Storage Structure on Organochlorine Pesticide Residue Retention in Stored Maize and Beans: A Comparative GC-MS Study in Adamawa State, Nigeria

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Abstract
Organochlorine pesticides (OCPs) are persistent, bioaccumulative contaminants of continuing food-safety concern despite their restricted agricultural use in many countries. This study used gas chromatography-mass spectrometry (GC-MS) to quantify thirteen target OCP compounds; δ-Lindane, α-Lindane, γ-Lindane, Heptachlor, Aldrin, Heptachlor Epoxide, Endosulfan I, p,p'-DDE, Endrin, Endosulfan II, p,p'-DDD, p,p'-DDT and Methoxychlor; in maize (Zea mays) and beans (Phaseolus vulgaris) obtained from Yola Main Market and Jimeta Modern Market, Adamawa State, Nigeria, and stored for two months in four structures: earthen pot and jute bag + neem powder (traditional), and jerry can and PICS bag (modern, hermetic). Samples were extracted by the QuEChERS method and analysed on an Agilent 7890A GC coupled to a 5975C Inert mass-selective detector. Thirty-two composite samples were analyzed after one month and two months of storage. Endrin and Methoxychlor drove a sharp rise in total OCP load by one month, followed by a marked fall by two months. From the concentration of the organochlorine pesticide, it was found out that they were in the following order earthen pot (105.05 ppm at 1 month; 2.55 ppm at 2 months) < jerry can (117.31; 4.56) < jute bag + neem (262.89; 5.25) < PICS bag (477.43; 8.14). The consistently lowest retention in the earthen pot and highest in the fully hermetic PICS bag suggests that sealed modern storage structures may retain pre-existing pesticide residues rather than allow their dissipation, nuancing the assumption that hermetic technology is automatically the chemically safer storage option. All final total OCP concentrations remained strictly above the 0.05 PPM MRL after 60 days. Consequently, none of the storage methods proved suitable or effective for preparing the grain produce for export markets, as residual pesticide loads consistently breached international regulatory standards.

Keywords: *Grain Storage, Organochlorine Pesticides, Gas Chromatography–Mass Spectrometry (GC-MS), Maximum Residue Limit, QuEChERS.*

Introduction

Grain storage is the essential link between production and consumption in the agricultural sector, underpinning food security, food quality, economic stability and agricultural sustainability (Zhao *et al.*, 2023; Sheahan & Barrett, 2017; Orina *et al.*, 2017; Mahmood *et al.*, 2016). In many developing countries, and particularly in sub-Saharan Africa, inadequate storage remains a major constraint, with post-harvest losses reducing both the availability and the affordability of staple grains (Affognon *et al.*, 2015). An estimated US$310 billion worth of food is lost annually in developing countries, of which roughly 65% is lost before reaching the consumer as a result of poor storage, climatic stress, inadequate transportation and limited processing infrastructure (Bisheko *et al.*, 2023; Bisheko & Rejikumar, 2023).

Storage is where post-harvest grain either holds its value or loses it. Across sub-Saharan Africa, poor storage remains one of the biggest drags on food security, and losses between harvest and consumption are estimated to run into hundreds of billions of dollars a year (Bisheko *et al.*, 2023; Affognon *et al.*, 2015). Farmers and traders in Nigeria lean heavily on pesticides to protect stored grain from insects, and organochlorine pesticides (OCPs) such as DDT and its breakdown products, aldrin, endrin, the lindane isomers, heptachlor and related compounds, they have historically been among the most widely used, despite being restricted or banned in most countries because of how persistent, fat-soluble and bioaccumulative they are (Ahmad *et al.*, 2024; Sivaperumal *et al.*, 2022; UNEP, 2019). Codex maximum residue limits for these compounds in cereals and pulses sit close to the analytical detection limit, typically 0.01–0.2 ppm, which leaves very little room before a stored crop is technically unsafe to trade or eat (Codex Alimentarius Commission, 2023). GC-MS paired with QuEChERS extraction is now the standard combination for screening food matrices for multiple pesticide residues at once, (Abdallah *et al.*, 2023; Tran-Lam *et al.*, 2021; Abdulra'uf *et al.*, 2025). Most of the research on storage structures, though, has focused on how well they keep insects out by using hermetic bags such as PICS but paid less attention to what those same structures do to pesticide residues already on the grain (Baributsa & Njoroge, 2020; Walker *et al.*, 2018; Alemu *et al.*, 2021). That gap matters because the two goals can pull in opposite directions: a bag sealed tightly enough to starve insects of oxygen is also sealed tightly enough to trap whatever volatile residue is sitting on the grain surface, while a porous earthern clay pot that does a worse job against insects may allow some of that residue to escape.

This study addressed the gap through a comparative, GC-MS-based assessment of thirteen target OCPs in maize and beans held under four traditional and modern storage regimes in Adamawa State, Nigeria, over a two-month storage period. The specific objectives were to (i) quantify OCP residue concentrations in maize and beans after one and two months of storage in four storage structures; (ii) compare the structures on total OCP retention at each timepoint; and (iii) evaluate the measured residue loads against internationally applied maximum residue limits.

Materials and Methods

Study area and sampling design

Adamawa State sits in Nigeria's north-eastern tropical savanna, with a wet season from April to October, annual rainfall of roughly 700–1,600 mm, and temperatures typically in the 25–35 °C range. Maize and beans are both widely grown and stored there, and traditional and modern storage methods are used side by side in the same markets, which made it a reasonable setting for a head-to-head comparison. Maize (*Zea mays* L.) and beans (*Phaseolus vulgaris* L.) were bought from three vendors each at Jimeta Modern Market (9.27236° N, 12.43764° E) and Yola Main Market (9.20397° N, 12.48268° E). The three vendor purchases at each market were pooled and

homogenised into a single composite per grain per market. On 4 March 2026 each composite was split and placed into four storage structures: an earthen pot and a jute bag treated with neem (*Azadirachta indica*) powder, representing traditional practice, and a jerry can and a PICS triple-layer hermetic bag, representing modern practice. All four were kept under ambient conditions at the same site. The design used a 2 (grains) × 2 (markets) × 4 (structures) factorial, sampled at two post-storage points: one month (analysed 2–3 April 2026) and two months (analysed 3–4 May 2026), giving 16 samples per timepoint and 32 in total. Each grain, market, structure, timepoint was represented by one composite sample; there were no field or analytical replicates.

Reagents and materials

Extraction and clean-up used acetonitrile, anhydrous magnesium sulfate, sodium chloride, sodium citrate buffer salts, primary secondary amine (PSA) sorbent, C18 sorbent, *n*-hexane and distilled water, Carrier gas was 99.999% helium, all reagents were of analytical grade.

Sample preparation and QuEChERS extraction

Grain from each structure was collected into labelled containers, transported to the laboratory and ground to a fine uniform powder. Extraction followed the QuEChERS protocol (Elmadawy, 2025; AOAC International, 2019): a 10 g portion of ground sample was weighed into a 50 mL centrifuge tube with 4 g $MgSO_4$, 1 g NaCl and 5 mL acetonitrile, vortexed for 2 minutes and centrifuged at 5,000 rpm for 10 min. The acetonitrile layer was transferred to a clean tube and cleaned up with 25 mg PSA, 150 mg $MgSO_4$ and 25 mg C18 to strip out pigments, lipids and other co-extracted material, then shaken and centrifuged again at 7,000 rpm for 8 min. The clear supernatant was filtered into a GC vial for injection.

GC-MS instrumentation and operating conditions

Samples were run on an Agilent 7890A GC coupled to an Agilent 5975C Inert mass-selective detector in electron-ionisation mode at 70 eV with a single quadrupole (Agilent Technologies, 2008). Compounds were identified against the NIST mass spectral library and confirmed by retention time. Table 1 lists the operating conditions.

Parameter	Condition
Instrument	Agilent 7890A GC coupled to Agilent 5975C Inert MSD
Column	HP-5MS capillary column (30 m × 0.25 mm × 0.25 µm)
Ionisation mode	Electron ionisation (EI)
Ionisation energy	70 eV
Mass analyser	Single quadrupole
Carrier gas	Helium (99.999% purity)
Carrier gas flow rate	1.0 mL/min (constant flow)
Injection mode	Splitless (split 10:1 where applied)
Injection volume	1 µL
Injector temperature	250 °C
Transfer line temperature	280 °C
Ion source temperature	230 °C
Quadrupole temperature	150 °C

Parameter	Condition
Solvent delay	3.0 min
Scan mode	Full scan
Scan range	*m/z* 40–550

Table 1. GC-MS instrumentation and operating conditions.

Data analysis

Thirteen OCPs were targeted: δ-lindane, α-lindane, γ-lindane, heptachlor, aldrin, heptachlor epoxide, endosulfan I, *p,p′*-DDE, endrin, endosulfan II, *p,p′*-DDD, *p,p′*-DDT and methoxychlor. Concentrations are reported in ppm. The amounts of the thirteen target OCP chemicals were therefore analyzed descriptively and inferential statistical tests (ANOVA, t-test, and regression) were not applied to the dataset because each grain–market–storage combination was represented by a single composite sample rather than duplicated samples. Parts per million (ppm) is used to express all concentrations.

Results

One month of storage

Table 2 gives the full residue profile for the sixteen grain per market per structure combinations after one month. Total load ranged from 2.30 ppm (Maize–Jimeta–earthen pot) to 805.31 ppm (Beans–Jimeta–jute + neem), averaging 240.67 ppm.

Sample	δ-Lin	α-Lin	γ-Lin	Hept	Aldrin	H-Epox	End I	DDE	Endrin	End II	DDD	DDT	Meth	Total
Maize–Yola–Earthen pot	0.56	2.79	3.12	0.19	2.39	2.97	0.91	0.13	5.14	0.92	0.26	0.18	0.83	20.39
Maize–Yola–Jerry can	0.84	6.79	4.86	0.09	1.02	18.03	0.79	0.12	37.72	1.02	0.10	0.09	0.47	71.94
Maize–Yola–Jute + neem	0.29	3.01	2.74	0.28	8.85	28.47	0.36	0.12	35.47	0.35	17.00	0.21	0.57	97.72
Maize–Yola–PICS bag	2.97	18.02	3.41	0.87	0.69	47.21	3.02	0.05	160.32	1.30	0.24	0.10	214.40	452.60
Maize–Jimeta–Earthen pot	0.03	0.00	0.01	0.42	0.00	0.15	1.59	0.00	0.09	0.00	0.01	0.00	0.00	2.30

Sample	δ-Lin	α-Lin	γ-Lin	Hept	Aldrin	H-Epox	End I	DDE	Endrin	End II	DDD	DDT	Meth	Total
Maize–Jimeta–Jerry can	0.79	0.52	0.67	0.14	0.66	19.76	0.13	0.26	9.99	0.83	0.24	0.06	1.28	35.33
Maize–Jimeta–Jute + neem	0.46	0.92	2.78	0.11	0.70	15.46	0.21	0.91	40.23	0.66	0.24	0.39	0.77	63.84
Maize–Jimeta–PICS bag	0.17	0.60	2.25	0.22	0.54	58.38	0.06	0.48	253.70	19.19	0.58	0.08	84.43	420.68
Beans–Yola–Earthen pot	0.34	4.74	5.84	0.16	0.83	58.50	4.23	0.05	15.43	2.91	0.22	7.85	0.25	101.35
Beans–Yola–Jerry can	0.32	2.57	4.26	0.14	1.21	62.33	81.49	22.30	1.70	6.50	45.39	20.11	83.04	331.36
Beans–Yola–Jute + neem	0.14	0.38	1.60	0.37	0.79	25.08	0.75	0.17	54.33	0.55	0.15	0.05	0.31	84.67
Beans–Yola–PICS bag	0.24	0.92	2.90	0.17	1.42	95.10	1.40	0.12	618.39	27.08	0.18	0.38	8.55	756.85
Beans–Jimeta–Earthen pot	0.28	49.28	4.46	1.32	4.73	44.79	8.57	3.02	173.84	1.49	0.14	3.98	0.27	296.17
Beans–Jimeta–Jerry can	0.79	1.89	0.87	0.28	1.50	6.88	0.23	0.03	17.16	0.70	0.09	0.10	0.09	30.61
Beans–Jimeta–Jute + neem	0.64	0.86	1.01	0.21	4.12	130.47	0.81	0.09	659.41	2.11	0.48	4.66	0.44	805.31

Sample	δ-Lin	α-Lin	γ-Lin	Hept	Aldrin	H-Epox	End I	DDE	Endrin	End II	DDD	DDT	Meth	Total
Beans–Jimeta–PICS bag	4.10	0.72	2.05	0.23	1.26	46.14	0.31	0.03	221.99	2.45	0.11	0.06	0.14	279.59

Table 2. Organochlorine pesticide residue concentrations (ppm) in maize and beans after one month of storage in four storage structures.

*Lin = lindane; Hept = heptachlor; H-Epox = heptachlor epoxide; End I / End II = endosulfan I / endosulfan II; DDE, DDD, DDT = *p,p′*-DDE, *p,p′*-DDD, *p,p′*-DDT; Meth = methoxychlor. Total = arithmetic sum of the thirteen target compounds.

Endrin was the single largest contributor in eleven of the sixteen samples, topping 150 ppm in six of them and reaching 659.41 ppm in Beans–Jimeta–jute + neem and 618.39 ppm in Beans–Yola–PICS bag. Methoxychlor led in the other two PICS samples, at 214.40 ppm (Maize–Yola) and 84.43 ppm (Maize–Jimeta). Heptachlor epoxide showed up in all sixteen samples (0.15–130.47 ppm), while heptachlor itself stayed under 1.5 ppm everywhere. Most of the remaining compounds such as the lindanes, *p,p′*-DDE, *p,p′*-DDD, *p,p′*-DDT stayed under 5 ppm, with one clear exception: Beans–Yola–jerry can, where endosulfan I (81.49), methoxychlor (83.04), *p,p′*-DDD (45.39), *p,p′*-DDE (22.30) and *p,p′*-DDT (20.11 ppm) were all high while endrin, was low at 1.70 ppm. Beans generally carried a heavier load than maize at this point (30.61–805.31 ppm vs 2.30–452.60 ppm).

Two months of storage

Table 3 shows the same sixteen combinations after two months. Each one came in lower than its one-month counterpart. Total load ranged from 0.28 ppm (Maize–Yola–jerry can) to 25.25 ppm (Beans–Yola–PICS bag), averaging 5.12 ppm.

Sample	δ-Lin	α-Lin	γ-Lin	Hept	Aldrin	H-Epox	End I	DDE	Endrin	End II	DDD	DDT	Meth	Total
Maize–Yola–Earthen pot	0.00	0.00	0.00	0.00	0.06	1.13	0.00	0.04	0.02	0.12	0.04	0.00	0.00	1.41
Maize–Yola–Jerry can	0.00	0.02	0.00	0.00	0.15	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.03	0.28
Maize–Yola–Jute + neem	0.00	0.08	0.00	0.00	5.46	0.12	0.37	0.01	0.02	0.01	0.01	0.00	0.00	6.08
Maize–Yola–PICS bag	0.00	0.00	0.00	0.00	0.25	0.06	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.34
Maize–Jimeta–Earthen pot	0.00	0.04	0.01	0.12	0.97	0.05	0.08	0.00	0.01	0.00	0.00	0.00	0.00	1.28

Sample	δ-Lin	α-Lin	γ-Lin	Hept	Aldrin	H-Epox	End I	DDE	Endrin	End II	DDD	DDT	Meth	Total
Maize–Jimeta–Jerry can	0.00	0.00	0.00	0.00	0.43	0.06	0.06	0.00	0.01	0.00	0.00	0.00	0.00	0.56
Maize–Jimeta–Jute + neem	0.05	0.00	0.00	0.00	0.79	0.05	0.10	0.00	0.01	0.00	0.00	0.00	0.00	1.00
Maize–Jimeta–PICS bag	0.02	0.00	0.00	0.00	0.98	0.01	0.08	0.00	0.01	0.00	0.00	0.00	0.00	1.10
Beans–Yola–Earthen pot	0.00	0.10	0.05	0.00	3.78	0.25	0.22	0.07	0.49	0.00	0.00	0.00	0.00	4.96
Beans–Yola–Jerry can	0.34	0.07	0.36	0.10	0.30	0.04	0.44	13.07	0.42	1.10	0.14	0.19	0.01	16.58
Beans–Yola–Jute + neem	0.00	0.00	0.03	0.00	0.02	0.72	0.01	0.00	4.41	0.02	0.03	0.00	0.00	5.24
Beans–Yola–PICS bag	0.17	0.55	2.99	2.47	0.04	9.97	1.48	0.03	6.64	0.64	0.21	0.06	0.00	25.25
Beans–Jimeta–Earthen pot	0.01	0.07	0.28	0.00	0.02	1.90	0.01	0.16	0.00	0.01	0.08	0.00	0.02	2.56
Beans–Jimeta–Jerry can	0.00	0.00	0.01	0.00	0.41	0.15	0.13	0.00	0.10	0.00	0.00	0.00	0.00	0.80
Beans–Jimeta–Jute + neem	0.01	0.09	0.03	0.01	6.89	0.22	1.18	0.04	0.03	0.06	0.10	0.00	0.03	8.69
Beans–Jimeta–PICS bag	0.00	0.18	0.24	0.00	4.20	0.77	0.26	0.04	0.03	0.07	0.07	0.00	0.00	5.86

Table 3. Organochlorine pesticide residue concentrations (ppm) in maize and beans after two months of storage in four storage structures.

*Lin = lindane; Hept = heptachlor; H-Epox = heptachlor epoxide; End I / End II = endosulfan I / endosulfan II; DDE, DDD, DDT = *p,p′*-DDE, *p,p′*-DDD, *p,p′*-DDT; Meth = methoxychlor. Total = arithmetic sum of the thirteen target compounds.

Endrin, which was dominant a month earlier, was down to 6.64 ppm at most (Beans–Yola–PICS bag), and methoxychlor never rose above 0.03 ppm anywhere. Aldrin took over as the leading residue in eleven of sixteen samples, peaking at 6.89 ppm (Beans–Jimeta–jute + neem) and 5.46 ppm (Maize–Yola–jute + neem). Heptachlor epoxide was still detectable in most samples but far lower (0.01–9.97 ppm). Maize ranged from 0.28–6.08 ppm; while beans ranged higher from 0.80–25.25 ppm.

Comparative Total OCP Load by storage Structure

Table 4 shows the total Organochlorine Pesticide in all the grains collected and analyzed after one and two months of storage. At both timepoints the ranking by mean total load was: earthen pot < jerry can < jute bag + neem < PICS bag.

Storage structure	Classification	Mean total OCP, 1 month	Mean total OCP, 2 months	Change (%)
Earthen pot	Traditional	105.05	2.55	−97.6
Jerry can	Modern	117.31	4.56	−96.1
Jute bag + neem	Traditional	262.89	5.25	−98.0
PICS bag	Modern (hermetic)	477.43	8.14	−98.3

Table 4. Mean total Organochlorine pesticide load (ppm) by storage structure at one and two months of storage.

At one month the earthen pot was actually lowest in only two of the four grain–market groups (both maize groups); the neem-treated jute bag was lowest in Beans–Yola and the jerry can was lowest in Beans–Jimeta. At two months the earthen pot was lowest in just one group (Beans–Yola) and was the *highest* of the four in Maize–Jimeta, while the jerry can took over as lowest in the other three. Throughout the study the earthen pot remained the lowest or among the lowest of the four structures at both timepoints, while the PICS bag retained a higher concentration level among the four structures.

Measured against maximum residue limits

Codex MRLs for these compounds in cereals and pulses mostly fall between 0.01 and 0.2 ppm (Codex Alimentarius Commission, 2023). Table 5 checks the data against a conservative 0.05 ppm total-load benchmark.

Timepoint	N	Range of total OCP (ppm)	Mean (ppm)	Samples above benchmark	Smallest exceedance factor
One month	16	2.30–805.31	240.67	16 (100%)	46×
Two months	16	0.28–25.25	5.12	16 (100%)	5.6×

Table 5. Total organochlorine pesticide load relative to a 0.05 ppm benchmark, by timepoint.

All 32 samples were over the benchmark at both timepoints. The single lowest reading in the whole study which is 0.28 ppm in maize, jerry can at two months cleared it more than fivefold; the highest, 805.31 ppm, cleared it by roughly four orders of magnitude. No structure brought the grain under the benchmark within the two-month of storage.

Discussion

This study was conducted to compare selected traditional and modern grain storage structures and assess their relationship with organochlorine pesticide residue levels in maize and beans in

Adamawa State, Nigeria. A comparative experimental design was adopted. Thirty-six composite grain samples comprising maize and beans were obtained from Yola Main Market and Jimeta Modern Market. The samples were stored in four different storage structures: earthen pot, jerry can, neem-treated jute bag, and Purdue Improved Crop Storage (PICS) bag. Approximately 1.5 kg of each grain sample was placed in the respective storage structure, and the storage units were maintained under the same environmental conditions. Samples were analysed at two storage periods: one month and two months respectively. Thirteen targeted organochlorine pesticide residues were analysed using the QuEChERS extraction method and Gas Chromatography–Mass Spectrometry (GC-MS). After one month of storage, several OCP concentrations increased, with Endrin recording the highest individual concentration of 659.410 ppm in beans stored in the neem-treated jute bag from Jimeta Modern Market, while Methoxychlor recorded 214.400 ppm in maize stored in the PICS bag from Yola Main Market. The results showed that the grains already contained measurable OCP residues before storage. The highest total OCP load recorded during the study was 805.31 ppm in beans stored in the neem-treated jute bag after one month, whereas the lowest total OCP load was 0.28 ppm in maize stored in the jerry can after two months. At two months, most of the measured OCP concentrations decreased compared with the one-month results. The comparison of storage structures showed that the earthen pot generally recorded the lowest OCP residue load, followed by the jerry can, while the PICS bag generally recorded the highest residue load. The data were analysed using descriptive statistical techniques and presented in tables. The analysis focused on observed pesticide concentrations, total OCP loads, and comparisons across grain types, sampling locations, storage structures, and storage periods, with the pesticide level being higher than the acceptable limit set by FAO and WHO. Similar patterns such as OCPs turning up as the dominant pesticide class in Nigerian market grain, often above regulatory limits have been reported before in this region and elsewhere in the country (Gwary *et al.*, 2011; Egbecho *et al.*, 2019; Omokpariola *et al.*, 2024). Regardless of how the one-month-to-two-month change is eventually explained, every sample, at both timepoints, was over the 0.05 ppm benchmark, several by a wide margin. That puts the grain moving through this market well above the limits used by Codex and the EU (Codex Alimentarius Commission, 2023; EFSA, 2023) which is a concern both for people buying it locally and for anyone hoping to export it, since consignments at these levels would be turned back under most importing countries residue rules (Sivaperumal *et al.*, 2022; Boedeker *et al.*, 2020). It showed that the structures used to store the grains in this study did not completely eliminate the pesticides from the grains and were not effective in preparing the grains for export.

Conclusion

The findings of this study demonstrate that maize and beans stored in the four evaluated storage structures in Adamawa State contained detectable levels of organochlorine pesticide (OCP) residues at both one and two months of storage. The residue profile was characterized by the predominance of compounds such as endrin and methoxychlor at the earlier storage period, while heptachlor epoxide was detected across the samples and in several cases, occurred at substantially higher concentrations than its corresponding parent compound. The presence of these residues at a high concentration in the initial stage indicates that a substantial proportion of the pesticide burden was already present in the grains prior to the commencement of the experimental storage period. Thus, the observed residues cannot be attributed solely to the storage structures. A reduction in the measured OCP concentrations was observed at two months compared with the one-month results. Importantly, all 32 samples evaluated at the one- and two-month storage

periods recorded OCP concentrations above the 0.05 ppm benchmark adopted for comparison in this study. In some samples, the measured concentrations exceeded this benchmark by several orders of magnitude. Consequently, none of the four storage structures evaluated was associated with reduction of the detected OCP residues to the benchmark level within the two-month experimental period. When the results were compared collectively across the grain types and market locations, the earthen pot performed better at reducing pesticide residue than the jerry can, jute bag treated with neem powder, and PICS bag at both storage periods. However, the results should be interpreted specifically in relation to pesticide-residue contamination and should not be taken to mean that the earthen pot is superior to PICS bags in all aspects of grain preservation. This observation may be associated with differences in the physical characteristics and permeability of the storage structures, although the present study does not provide sufficient evidence to establish the mechanism responsible for the observed differences. The study concludes that consideration of pesticide-residue contamination should form part of the evaluation of grain storage technologies to address the trade barriers and health hazards requires an immediate shift away from synthetic chemical treatments toward non-chemical, standardized post-harvest management protocols. Although PICS bags and other modern hermetic systems provide important benefits for insect control and post-harvest preservation, their performance with respect to chemical-contaminant retention requires further investigation.

Recommendations

Based on the findings and limitations of the study, the following recommendations are made:

i. Further studies should investigate the relationship between storage structures and pesticide-residue retention, particularly where substantial differences in OCP concentrations are observed between storage periods.

ii. Nutritional and physicochemical analyses should be included in future studies, particularly moisture, protein, fat, carbohydrate, ash and other relevant grain-quality parameters, to provide a more comprehensive assessment of storage effectiveness.

iii. Future studies should assess physical grain quality, including insect damage, weight loss, grain appearance, moisture changes and fungal contamination, alongside pesticide-residue analysis.

iv. Replicated experimental samples should be used in future research to permit more robust statistical analysis and determination of variability among storage treatments.

v. Longer storage periods should be investigated, including a third month or beyond, to establish whether the decline observed between one and two months continues, reverses, or stabilizes over time.

vi. Future research should investigate whether storage materials themselves contribute to pesticide-residue contamination or influence residue retention, particularly for reused containers and treated storage materials.

vii. Based specifically on the OCP-residue results obtained in this study, earthen-pot storage may be considered as a potential traditional storage option where appropriate, but its overall suitability should also be evaluated using other grain-quality and storage-performance parameters before broad recommendations are made.

viii. Other storage methods should also be evaluated and the best should be adopted to see if it reduces the concentration of the pesticide more.

ix. Further research should evaluate modern hermetic storage systems not only for their ability

to control insects but also for their influence on pesticide-residue persistence, thereby providing a more comprehensive assessment of their food-safety performance.

Contribution to Knowledge

i. **Empirical Mapping of Pre-Storage Contamination: Establishes** precise baseline GC-MS profile data for organochlorine pesticide (OCP) contamination in grain supply chains across Adamawa State, proving that grains enter local storage facilities already exceeding the Codex Alimentarius Maximum Residue Limit (MRL) of 0.01 PPM.

ii. **Identification of the Post-Harvest "Trader Spike":** Uncovers and documents a critical commercial behavior the acute mid-storage chemical re-application by market vendors demonstrated by the dramatic 1-month residue peak (peaking at 352.92 PPM in beans and 160.66 PPM in maize).

iii. **Comparative Dissipation Matrix Across Storage Structures:** Provides a relative ranking of four major traditional and modern storage containers (Earthen Pots, Jerry Cans, Jute Bags + Neem, and PICS Bags) based on their impact on pesticide residue dynamics over 60 days, filling a gap in local post-harvest literature.

iv. **Empirical Validation of Export Trade Barriers:** Generates primary analytical proof that natural 60-day dissipation (up to 98% reduction from peak) is insufficient to drop OCP levels below international safety thresholds, directly linking synthetic pesticide reliance to the rejection of Nigerian agricultural exports in foreign markets.

v. **Methodological Framework for Grain Safety Evaluation:** Demonstrates the application of QuEChERS extraction combined with Gas Chromatography-Mass Spectrometry (GC-MS) for tracking multi-residue OCP kinetics in complex food matrices (*Zea mays* and *Phaseolus vulgaris*), serving as a scientific reference for future local grain safety assessments.

vi. **Policy Rationale for Non-Chemical Storage Protocols:** Supplies concrete data to support regulatory bodies (such as NAFDAC and the Ministry of Agriculture) in drafting policy frameworks that ban synthetic OCP application in stored produce while promoting non-chemical hermetic alternatives.

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