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Biomonitoring of Organophosphate Pesticide Exposure among Smallholder Farmers in Nigeria: A Mixed-Methods Study of Knowledge, Practices, Gap in Perceived Safety and Internal Dose

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ABSTRACT

Introduction: Pesticide poisoning is a critical public health challenge in low-income countries, yet biomonitoring data to quantify exposure is severely scarce. Globally, pesticide poisoning affects approximately 41 million people annually with a minimum 300,000 deaths, leading to health problems as a result of the exposures. This study moves beyond self-reported practices to biochemically assess the extent of pesticide exposure among smallholder farmers in Abuja, Nigeria, and explores the concerning gap between perception and reality.

Methods: A mixed-methods approach was employed, including a cross-sectional survey (n=308), 8 focus group discussions (FGDs), and gas chromatography-mass spectrometry (GC-MS) analysis of six urinary dialkylphosphate (DAP) biomarkers in a subset of 54 farmers.

Results: Biomonitoring confirmed universal internal exposure: urinary diethylphosphate (DEP) and diethylthiophosphate (DETP) were detected in 100% of farmers, with three additional dialkylphosphate metabolites present in 85–94% of the cohort. This contamination starkly aligns with prevalent unsafe practices. While 90% prioritized pesticide effectiveness, only 47.7% could correctly define Personal Protective Equipment (PPE). Critically, 86% experienced pesticide spillage onto skin or eyes, and only 3.9% stored pesticides safely. FGDs revealed that economic constraints, learned behaviors from family, and ineffective vendor advice perpetuate this high-risk cycle.

Conclusion and Implications: The study provides objective biochemical evidence that contradicts self-reported safety perceptions. There is a dangerous dissonance between farmers' operational priorities and their documented toxic exposure. Interventions must extend beyond basic awareness campaigns to address the systemic and socioeconomic drivers of unsafe practices. We advocate for farmer-centered training, strict enforcement of pesticide regulations, and promotion of Integrated Pest Management (IPM) to translate knowledge into measurable reductions in exposure.

KEYWORDS: Pesticides, Smallholder Farmers, Biomonitoring, Dialkylphosphates, Biomarkers

INTRODUCTION

Pesticide exposure remains a major yet under-recognised public health problem, disproportionately affecting low- and middle-income countries (LMICs). Globally, an estimated 41 million cases of pesticide poisoning occur annually, with at least 300 000 deaths, approximately 99% of which are reported from LMICs.[1, 2] Pesticides are toxic chemical substances deliberately introduced into the environment to control unwanted plant and animal species during agricultural production, storage, and distribution.[3,4] Smallholder farmers are among the most vulnerable occupational groups due to frequent handling of pesticides, limited access to personal protective equipment (PPE), inadequate training, and weak regulatory enforcement. Their farming systems are typically labour-intensive, resource constrained, and heavily dependent on chemical pesticides to maintain productivity and minimise crop losses.[4]

In Nigeria, smallholder farmers constitute over 80% of the agricultural workforce and account for nearly 98% of national food production. Agricultural productivity in this setting relies heavily on chemical pesticides, often applied under unsafe conditions. Although Nigeria is a signatory to international conventions regulating pesticide use and has national regulatory frameworks overseen by the National Agency for Food and Drug Administration and Control (NAFDAC), enforcement is weak and highly hazardous pesticides remain accessible. These systemic gaps increase occupational exposure through dermal contact, inhalation, and ingestion of contaminated food and water. [1, 5, 6, 7]

The health consequences of pesticide exposure range from acute poisoning characterised by neurological, respiratory, and gastrointestinal symptoms to chronic outcomes including peripheral neuropathy, endocrine disruption, infertility, immune dysfunction, and neurodegenerative diseases. Beyond individual morbidity and mortality, pesticide poisoning imposes substantial economic and social burdens through healthcare costs, productivity losses, and household impoverishment. [8, 9, 10]

Most studies assessing pesticide exposure among Nigerian farmers rely on self-reported practices and symptoms, which are subject to recall bias and exposure misclassification. This study's use of biomonitoring is therefore a critical advancement. Biomonitoring provides a more objective measure of internal dose by integrating exposure across multiple routes. [6, 11, 12] Urinary dialkylphosphate (DAP) metabolites are widely used biomarkers of organophosphate pesticide exposure and offer a robust tool for population-level exposure assessment. [11, 12] However, biomonitoring data among Nigerian smallholder farmers remain scarce.

This study aimed to quantify pesticide exposure using urinary DAP biomarkers and to examine the disconnect between perceived safety practices and objectively measured exposure among smallholder farmers in Abuja, Nigeria, using a mixed-methods public health approach.

METHODS

Study Design and Setting

We conducted a descriptive cross-sectional mixed-methods study among smallholder farmers in three area councils (Gwagwalada, Bwari, and Kuje) in Abuja, Nigeria.

Study Population

Smallholder farmers aged 18–75 years cultivating farmland between <1 and 10 hectares, who had handled or applied pesticides for at least six months and had resided in the study area for a minimum of six months, were eligible. Farmers with communication impairments affecting informed consent or those receiving treatment for acute pesticide poisoning at the time of data collection were excluded.

Sample Size and Sampling

The quantitative sample size was estimated using Cochran's formula for prevalence studies.[12] Confidence level of 95%, and precision of 5% were used. After adjusting for non-response, 308 farmers were recruited.

A multistage sampling technique was used. Three area councils were selected out of the six area councils in the FCT Abuja by simple random sampling, followed by random selection of wards and farming communities. Farming settlements ("*angwas*") were treated as clusters, and all eligible farmers within selected clusters were invited to participate until the sample size was achieved.

For biomonitoring, the 54 participants selected were drawn from the broader survey sample of 308 using a systematic household-based sampling approach. Households were selected randomly from among the farming settlements (angwas) already included in the quantitative survey, and urine specimens were collected from all eligible members within each selected household. This approach ensured that the biomonitoring subsample was embedded within the same sampling frame as the parent survey, minimising selection bias while remaining logistically feasible given laboratory cost constraints. The subsample size is consistent with prior organophosphate biomonitoring studies that have demonstrated adequate exposure characterisation with samples of 40 to 60 participants. [14, 15]

DATA COLLECTION

Quantitative Survey

Data were collected using a semi-structured, interviewer-administered questionnaire covering socio-demographic characteristics, knowledge of safe pesticide use, handling and protective practices, and factors influencing exposure.

Questionnaire content validity was assessed by experts in Community Medicine Department, and test–retest reliability demonstrated excellent reliability (intraclass correlation coefficient = 0.90).

Qualitative Component

Eight focus group discussions (FGDs) were conducted with 48 participants purposively selected and stratified by sex and age. Discussions lasted 60 to 90 minutes, were audio-recorded, and guided by a semi-structured topic guide. Data collection continued until thematic saturation was achieved.

Biomonitoring and Laboratory Analysis

Midstream urine samples (10 mL) were collected in sterile polypropylene containers, stored in cold conditions at -40°C. Specific-gravity corrected method was used as standard for spot urine internal standards, and samples were analysed for six dialkylphosphate (DAP) metabolites of dimethyl phosphate (DMP), dimethyl thiophosphate (DMTP), dimethyl dithiophosphate (DMDTP), diethyl phosphate (DEP), diethyl thiophosphate (DETP), and diethyl dithiophosphate (DEDTP). [17, 18]

Samples were extracted using a QuEChERS-based method and analysed by gas chromatography–mass spectrometry (GC-MS). Quality assurance measures included matrix-matched calibration curves, procedural blanks, and internal standards. [19, 20, 21]

It must be acknowledged that DAPs (DMP, DEP, etc.) are shared metabolites of multiple organophosphate parent compounds and can also arise from environmental pre-formation (i.e., non-pesticide dietary exposure).

Data Analysis

Quantitative data were analysed using SPSS version 26. Descriptive statistics summarised participant characteristics and exposure indicators. Knowledge and practice scores were derived using binary scoring and classified as "good" or "poor" based on a 50% cut-off. The associations between the socio-demographic variables and pesticide exposure, knowledge, practices were assessed using chi-square tests and multivariable logistic regression. Statistical significance was set at $p<0.05$.

Qualitative data were transcribed verbatim and analysed inductively using thematic content analysis. Codes were grouped into sub-themes and overarching themes aligned with study objectives.

Ethical Considerations

Ethical approval was obtained from the University of Abuja Teaching Hospital Human Research Ethics Committee (FCT/UATH/HREC/13088). Written informed consent was obtained from all participants. Confidentiality, voluntary participation, and non-maleficence were ensured throughout the study.

RESULTS

Study Participants

All 308 eligible smallholder farmers were approached and informed consent was obtained, prior to enrolment, giving a response rate of 100%. The mean (±SD) age of participants was 43.8 ± 14.6 years (range: 18 to 75 years), with the largest proportion aged 40 to 49 years (28.9%). Two-thirds of participants were male (66.6%), and majority were married (74.3%) and belonged to the Gbagyi ethnic group (44.2%). Nearly half (45.5%) had completed secondary education, while 7.1% had no formal education. Over half (52.9%) cultivated farms of 1 to 4 hectares.

Farming Characteristics and Crop Types

Almost all respondents (98.7%) cultivated multiple crops concurrently. Maize, rice, beans, and yam were the most commonly grown crops. Most farmers (66.6%) had used pesticides for more than 10 years, reflecting long-term occupational exposure.

Knowledge of Pesticide Safety

Knowledge of pesticide terminology was high: 99.4% correctly defined pesticides. However, understanding of personal protective equipment (PPE) was limited, with only 47.7% correctly identifying PPE as equipment used to minimise exposure to hazards. While 68.2% recognised PPE as protective, misconceptions persisted, including viewing personal clothing as PPE.

Most respondents (91.9%) obtained pesticide-related information informally from fellow farmers, while fewer reported formal sources such as workshops (24.4%) or agricultural extension services (8.8%). Although 96.1% reported that pesticide effectiveness was the primary determinant of product choice, very few considered human health (2.9%) or environmental impact (1.3%) of pesticides.

Overall, 66.9% of participants were classified as having good knowledge of safe pesticide use, while 33.1% demonstrated poor knowledge. Knowledge of pesticide use was predominantly acquired informally through family members and vendors, with minimal formal training

Safe Farming Practices

Although 62.0% reported using some form of PPE during pesticide application, only 44.5% reported consistent use. Face masks were the most commonly used item (21.8%), followed by gloves (19.2%) and boots (15.9%). Nearly all respondents practised post application hygiene, including immediate hand washing (99.0%), changing clothes (98.7%), and bathing (98.4%).

Backpack or knapsack sprayers were used by 96.1% of respondents, and spot treatment was the predominant application method (95.8%). Despite frequent pesticide application with 38.0% reporting "always" applying pesticides, only 3.9% stored pesticides appropriately in designated storage facilities. Disposal practices were suboptimal: 26.3% discarded containers in the bush and 22.4% burned them.

Based on composite scoring, 55.8% of farmers demonstrated good safe farming practices, while 44.2% had poor practices. . Economic constraints, limited access to PPE, and lack of government support were consistently cited as barriers to safe practices.

Factors Influencing Pesticide Exposure

Effectiveness against pests was the most commonly cited factor influencing pesticide choice (49.8%), followed by availability (38.0%) and cost (12.2%). Although 76.9% reported no difficulty reading label instructions and 84.7% followed label guidance when calculating pesticide quantities. Direct exposure to pesticides were common, with 86.0% reported pesticide spills with contact involving the skin, eyes, nose, or mouth. Only 23.4% had ever received formal training on pesticide handling and safety. Participants described personal experiences of skin burns, eye irritation, and nausea, reinforcing awareness of health risks, yet unsafe practices persisted due to cost, habit, and lack of alternatives.

Sociodemographic correlates of Pesticide Exposure

Pesticide exposure was significantly associated with age (p=0.023), sex (p=0.010), marital status (p=0.030), ethnicity (p=0.036), religion (p=0.040), education level (p<0.001), and farm size (p=0.003). Income and smoking status were not significantly associated with exposure. Overall, 265 respondents (86.0%) were classified as exposed to pesticides.

Knowledge, Practices, and Exposure

Poor knowledge of safe pesticide use was significantly associated with pesticide exposure (p=0.004), as were poor safe farming practices (p=0.001). Farmers with inadequate safety practices had a higher likelihood of exposure compared with those reporting good practices.

Predictors of Pesticide Exposure

Multivariable logistic regression analysis, independent predictors of pesticide exposure included younger age (<20 years), marital status, farm size, poor knowledge of pesticide safety, and poor farming practices. Farmers with poor safety practices had nearly twice the odds of exposure to pesticides (adjusted OR 1.9, 95% CI 1.2–5.9), while poor knowledge was also independently associated with exposure to pesticides (adjusted OR 1.6, 95% CI 1.3–6.9).

Biomonitoring Results

Urinary biomonitoring of 54 farmers demonstrated widespread internal exposure to organophosphate pesticides. Diethylphosphate (DEP) and diethylthiophosphate (DETP) were detected in all urine samples (100%), with median concentrations of 0.40 µg/L and 0.99 µg/L, respectively. Dimethyl phosphate (DMP) was detected in 94.4% of samples with a median concentration of 0.18 µg/L, while dimethylthiophosphate (DMTP) and dimethyldithiophosphate (DMDTP) were detected in 87.0% and 85.2% of samples, with median concentrations of 0.03 µg/L and 0.02 µg/L, respectively. Overall, DEP, DETP, and DMP demonstrated the highest median concentrations among the measured dialkyl phosphate metabolites, indicating a higher relative burden of exposure to organophosphate pesticides in the study population.

Biomarkers, Knowledge, and Practices

There was no statistically significant association between knowledge level and urinary concentrations of DMP, DMTP, or DMDTP (all p>0.05). However, safe farming practices were significantly associated with lower detection of DMP (p=0.023), suggesting that behavioural practices may reduce internal exposure, even when knowledge alone does not.

Table 1: Knowledge Regarding the Safe Usage of Pesticides I *

Variables	Frequency(n=308)	Percent
Can you define the term 'pesticides'		
Yes	306	99.4
No	2	0.6
Type of pests commonly encounter on the farm		
Insects	303	98.4
Weeds	264	85.7
Rodents	233	75.6
Fungi	40	13.0
Main source of information on pesticide uses and safety		
Fellow Farmers	283	91.9

Workshops/seminars	75	24.4
Internet	68	22.1
Agricultural extension services	27	8.8
Others	3	1.0
Factors respondents considered when selecting pesticides for crops		
Effectiveness against targets pest	296	96.1
Costs	20	6.5
Potential harm to human	9	2.9
Environmental Impact	4	1.3
Types of pesticides known by respondents		
Herbicides	148	48.1
Insecticides	167	54.2
Rodenticides	10	3.2
Fungicides	4	1.3
Duration of Pesticides usage		
Less than 1 year	2	0.6
1-5 years	20	6.5
6-10 years	81	26.3
>10 years	205	66.6
Knowledge of Personal Protective Equipment		
Equipment worn to minimize exposure to hazards	147	47.7
Personal cloths	147	47.7
Agricultural company's cloth	6	1.9
I don't know	8	2.6
Reasons for use of PPE while applying pesticides		
For Protection against pesticides exposure	210	68.2
For Prevention of injuries:	87	28.2
Prevention from inhaling pesticides	11	3.6
The examples of PPEs		
Facemask	235	76.3
Gloves	123	39.9
Boots	104	33.8
Full body suit	73	23.7
Apron	21	6.8
Helmet	21	6.8
I do not know	6	1.9
Reading safety instructions on pesticide containers before use is important		
Yes	296	96.1
No	12	3.9
Checking for the expiring date (colour code) is important before using pesticides		
Yes	300	97.4
No	8	2.6

-Multiple Responses

Table 2: Safe Farming Practices among Smallholder Farmers I *

Variables	Frequency(n=308)	Percent
Use Personal Protective Equipment		
Yes	191	62.0
No	117	38.0
Use Personal Protective Equipment rate		
Always	137	44.5
Occasionally	54	17.5
Type of Personal Protective Equipment used while applying pesticide and during farming activity		
Face mask	67	21.8

Safety gloves	59	19.2
Boots	49	15.9
Nose mask	16	5.2
Glasses	12	3.9
Aprons	4	1.3
Raincoat	1	0.3
Shoes	1	0.3
Full body suit	1	0.3
Overalls	1	0.3
Wash hands immediately after pesticides application		
Yes	305	99.0
No	3	1.0
Take bath immediately after applying pesticides		
Yes	303	98.4
No	5	1.6
Change clothes immediately after pesticides application		
Yes	304	98.7
No	4	1.3
Use pesticides equipment while handling and applying pesticides		
Yes	304	98.7
No	4	1.3
Type of spraying equipment used		
Backpack Sprayer/ Knapsack	296	96.1
Sprayer	8	2.6
Method(s) of application used in applying these chemicals		
Spot treatment for specific weeds	295	95.8
Drenching system	51	16.6
Foliar system	5	1.6
Wiper system	3	1.0
Band spraying	1	0.3

- Multiple Responses

Table 3: Logistic regression analysis to determine the Predictors of Pesticide exposure among the respondents

Factors	P-value	Crude OR(CI)	P-value	Adjusted OR(CI)
Age group (Years)				
<20	0.033*	4.8(1.1-20.3)	0.016*	3.4(1.2-18.8)
20-29	0.231	3.2(0.5-21.7)	0.479	1.1(0.8-22.6)
30-39	0.283	2.0(0.6-7.1)	0.173	1.5(0.2-11.3)
40-49	0.294	0.2(0.01-4.2)	0.245	0.6(0.2-11.5)
50-59	0.760	1.2(0.4-3.5)	0.509	0.7(0.3-4.8)
≥60[RC]				
Sex				
Male[RC]				
Female	0.019*	0.3(0.1-0.8)	0.013*	2.9(1.4-6.8)
Marital status				
Married[RC]				
Unmarried	0.038*	5.3(1.1-25.4)	0.006*	2.5(1.3-19.4)
Ethnicity				
Gbagyi[RC]				
Bassa	0.689	1.3(0.3-5.7)	0.468	1.5(0.5-4.4)
Hausa	0.213	5.4(0.4-78.3)	0.140	2.3(0.7-6.7)
Yoruba	0.755	0.7(0.1-5.5)	0.184	2.2(0.7-7.1)
Igbo	0.890	1.2(0.1-13.0)	0.475	1.5(0.5-4.4)
Nupe	0.412	0.5(0.1-2.9)	0.118	2.4(0.8-7.3)
Tiv	0.559	0.6(0.1-2.9)	0.164	2.3(0.7-7.6)
Others	0.399	3.2(0.2-49.9)	0.610	1.1(0.7-1.8)
Religion				

Christianity^{RC}				
Islam	0.148	0.4(0.1-1.4)	0.497	1.2(0.7-1.9)
Highest level of education				
None	0.156	9.3(0.4-19.3)	0.331	2.5(0.6-11.9)
Primary	0.204	4.8(0.4-54.6)	0.196	3.7(0.5-61.2)
Secondary	0.072	7.7(0.8-71.3)	0.642	1.2(0.5-2.8)
Tertiary	0.312	2.9(0.4-24.8)	0.585	1.2(0.6-2.5)
Post Graduate^{RC}				
Size of your farm				
< 1 hectare	0.001*	0.2(0.1-0.5)	0.013*	1.7(1.1-2.6)
≥ hectares^{RC}				
Knowledge regarding safe pesticides use				
Good^{RC}				
Poor	0.041*	3.3(1.1-9.1)	0.042*	1.6(1.3-6.9)
Safe farming practices				
Good^{RC}				
Poor	0.038*	2.4(1.1-6.1)	0.025*	1.9(1.2-5.9)

****Significant at 95%*** ^{RC}***-Reference Category*** ***OR-Odd Ratio***

Note: Some subgroup categories had sparse cell counts resulting in wide confidence intervals,

Table 4: Identification and Quantity of Biomarkers of Pesticides Exposure in the Urine of the respondents

Variables	Frequency(n=54)	Percent	Mean±SD µg/L	Median (IQR) µg/L	Range µg/L
Dimethyl phosphate (DMP)					
Present	51	94.4	0.20±0.1	0.18(0.2)	0.0-0.84
Absent	3	5.6			
Dimethyl thiophosphate (DMTP)					
Present	47	87.0	0.19±0.6	0.03(0.1)	0.0-4.33
Absent	7	13.0			
Dimethyldithiiphosphate (DMDTP)					
Present	46	85.2	0.02±0.02	0.02(0.02)	0.0-0.18
Absent	8	14.8			
Diethylphosphate (DEP)					
Present	54	100.0	0.87±1.8	0.40(0.7)	0.01-12.2
Absent	0	0.0			
Diethylthiophosphate (DETP)					
Present	54	100.0	1.02±0.4	0.99(0.4)	0.07-2.39
Absent	0	0.0			

SD-Standard deviation ***IQR-Interquartile range***

Table 5: Urinary Dialkylphosphate (DAP) Biomarker Concentrations Compared to NHANES US General Population Reference Values

Biomarker	**NHANES LOD (µg/L)**	**Study Detection Rate (n=54)**	**Study Median (IQR) µg/L**	**NHANES ReferenceValue (µg/L)**	**Comparison Remarks**
Dimethyl phosphate (DMP)	0.58	94.4%	0.18 (0.2)	95th percentile: *13 µg/L	Study median well below the NHANES 95th percentile for the US general population.
Dimethyl thiophosphate (DMTP)	0.55	87.0%	0.03 (0.1)	GM1.85 µg/L; 95th percentile: 46 µg/L (Barr et al. 2004)†	Study median considerably below the NHANES 1999–2000 geometric mean of 1.85 µg/L.

Biomarker	NHANES LOD (µg/L)	Study Detection Rate (n=54)	Study Median (IQR) µg/L	NHANES ReferenceValue (µg/L)	Comparison Remarks
Dimethyl dithiophosphate (DMDTP)	0.51	85.2%	0.02 (0.02)	95th percentile: 19 µg/L (Barr et al. 2004)†	Study median substantially below the NHANES 95th percentile.
Diethyl phosphate (DEP)	0.37	100%	0.40 (0.7) [range: 0.01–12.2]	GM: 1.04 µg/L; 95th percentile: 13 µg/L (Barr et al. 2004)†	Study median (0.40 µg/L) is below the NHANES geometric mean (1.04 µg/L), reflecting low median exposure. however, the range extending to 12.2 µg/L approaches the NHANES 95th percentile (13 µg/L)
Diethyl thiophosphate (DETP)	0.56	100%	0.99 (0.4)	95th percentile: 2.2 µg/L (Barr et al. 2004)	Study median of 0.99 µg/L approaches the NHANES 95th percentile of 2.2 µg/L, indicating that the typical farmer in this study has DETP concentrations comparable to the most highly exposed individuals in the US general population.

Table footnotes:

LOD = Limit of Detection; GM = Geometric Mean; IQR = Interquartile Range; NHANES = National Health and Nutrition Examination Survey. DAP metabolites are non-specific biomarkers and may reflect exposure to multiple organophosphate parent compounds or pre-formed environmental metabolites. Individual parent pesticides cannot be identified from urinary DAP concentrations alone.

**Reference values are drawn from Barr DB et al. (2004),[29] Environ Health Perspect. 112(2):186–200 (doi: 10.1289/ehp.6503), reporting DAP metabolite concentrations in 1,949 urine samples from the US general population aged 6–59 years, NHANES 1999–2000. Geometric means were calculated only for metabolites with detection frequencies ≥60%; 95th percentile values are reported for all six metabolites. These represent a non-occupationally exposed general population comparator; direct risk quantification from these comparisons is not possible in the absence of universally accepted health-based biological limit values for individual urinary DAP metabolites.*

DISCUSSION

This study provides biomarker-based evidence of widespread organophosphate pesticide exposure among smallholder farmers in Abuja, Nigeria, and highlights a substantial disconnect between perceived safety and objectively measured internal dose. Despite relatively high self-reported knowledge and long-term pesticide use, five urinary dialkylphosphate (DAP) metabolites, particularly diethylphosphate (DEP) and diethylthiophosphate (DETP), were detected in all 54 biomonitored participants. These findings indicate that pesticide exposure is common and is likely underestimated when assessed using self-reported practices alone. Although 99.4% of farmers demonstrated basic knowledge of pesticides, this did not translate into reduced internal exposure, indicating that knowledge alone is insufficient to mitigate the risk. Although most farmers correctly defined pesticides and reported reading label instructions, fewer than half accurately understood personal protective equipment (PPE), and consistent PPE use was uncommon. This gap between general awareness and practical safety knowledge is critical, and similar findings have been reported in studies from the United States and other agricultural settings. 22, 23

THE BIOMONITORING EVIDENCE AND PUBLIC HEALTH RELEVANCE

Urinary biomonitoring confirmed universal internal exposure, with DEP and DETP detected in 100% of samples, and DMP, DMTP, and DMDTP detected in 94.4%, 87.0%, and 85.2% of samples respectively. While study median concentrations for most metabolites fell below NHANES 1999–2000 geometric means for the US general population, detection frequencies were substantially higher across all five metabolites. Most strikingly, universal detection of both DEP and DETP contrasts with frequencies of 71% and approximately 50–60% respectively in NHANES 1999–2000, and the DETP study median of 0.99 µg/L approaches the NHANES 95th percentile of 2.2 µg/L, indicating that the typical farmer in this cohort has DETP concentrations comparable to the most highly exposed individuals in the US general population. 29 Comparable detection patterns have been reported in population-based studies in high-income countries[23] and other low and middle income countries, although biomonitoring data from sub-Saharan Africa remain limited. [24]

Among the measured metabolites, DEP, DETP, and DMP exhibited the highest median concentrations, indicating that diethyl- and dimethyl-phosphate exposure pathways represent the dominant contributors to overall organophosphate burden in this study population. This pattern is consistent with agricultural settings where organophosphate compounds such as chlorpyrifos, diazinon, malathion, and parathion derivatives are commonly used. The detection of DMTP and DMDTP at comparatively lower median concentrations (0.03 µg/L and 0.02 µg/L, respectively) may reflect either lower exposure to their parent compounds or greater variability in metabolism and urinary excretion; however, their high detection frequencies above 85% indicate substantial population-level exposure. It is important to note that urinary DAP metabolites are non-specific biomarkers of exposure, they do not permit identification of individual parent organophosphate pesticides, and may also arise from environmental pre-formation or dietary sources unrelated to direct pesticide application.[17, 18]

Interpretation of urinary DAP concentrations is further constrained by the absence of universally accepted health-based biological limit values for individual metabolites such as DMP, DMTP, DMDTP, DEP, and DETP. Interpretation is therefore based on comparison with reference population distributions, such as NHANES, and international biomonitoring frameworks including Human Biomonitoring (HBM) guidelines. Within this context, the consistently high detection frequencies and elevated median concentrations observed in this study suggest exposure levels well above the background environmental exposure commonly reported in non-occupational populations. Furthermore, urinary DAP metabolites have short biological half-lives and primarily reflect recent exposure, indicating that the observed levels likely represent ongoing and repeated contact with organophosphate pesticides. The absence of a statistically significant association between years of pesticide use and biomarker levels further supports this interpretation and reinforces the importance of timing and frequency of exposure rather than cumulative duration alone. Given the known associations between chronic low-level organophosphate exposure and adverse neurobehavioural, endocrine, and reproductive outcomes, these results underscore the need for strengthened regulatory enforcement, improved pesticide handling practices, and targeted community education on exposure prevention. [8, 9, 10]

THE KNOWLEDGE–PRACTICE GAP AND STRUCTURAL DRIVERS OF EXPOSURE

Although most farmers demonstrated basic awareness of pesticide use, fewer than half accurately understood PPE, and consistent use was limited. This knowledge–practice gap likely reflects structural constraints rather than individual negligence. Economic barriers, limited access to affordable protective equipment, poor availability in rural markets, and reliance on informal information sources, such as family members, vendors, and peers, collectively constrain the adoption of safe practices. Knowledge alone was not associated with reduced biomarker levels, whereas safer farming practices were linked to lower detection of specific metabolites, suggesting that behaviour is a more important determinant of exposure than knowledge alone. This finding is consistent with evidence from a study among Latina farmworkers in south-western Idaho. [22]

FGD participants in this study explicitly described how pesticide application techniques and product selection were learned by observing family members and neighbours rather than through formal instruction, a pattern directly reflected in the quantitative finding that 91.9% of farmers identified fellow farmers as their primary source of pesticide information, with only 8.8% citing agricultural extension services. This socially transmitted knowledge system, shaped by economic necessity rather than safety evidence, likely explains why good knowledge scores did not translate into reduced biomarker levels, whereas behavioural practices — the domain most directly shaped by observed peer habits — were significantly associated with lower urinary DMP concentrations ($p=0.023$). These findings are consistent with studies across Africa and Asia showing that informal learning systems, combined with weak extension services, are major contributors to unsafe pesticide handling.[25, 26, 27]

THE UNSAFE PRACTICES AND EXPOSURE PATHWAYS

Multiple high-risk exposure pathways were identified in this study. The widespread use of knapsack sprayers, often poorly maintained, likely contributes to dermal and inhalational exposures. Alarmingly, 86.0% of farmers reported direct dermal or ocular contact with pesticides despite widespread post-application hygiene practices such as hand washing and bathing. These measures are insufficient to mitigate exposure occurring during mixing, application, and equipment failure. The observed statistically significant association between safe farming practices and reduced urinary DMP levels reinforces the importance and protective value of proper handling behaviours. These findings align with evidence from Egypt and other low-resource settings suggesting that low-cost behavioural interventions such as improved mixing techniques and equipment maintenance, may reduce exposure more effectively than PPE use alone.[28]

Qualitative data provided important mechanistic context for the high rates of direct exposure documented quantitatively. FGD participants described pesticide spillage as routine and largely unavoidable, attributing it to poorly maintained knapsack sprayers and the absence of affordable replacement parts which is consistent with the survey finding that 86.0% of farmers reported dermal or ocular pesticide contact. Critically, participants also described post-application hygiene practices such as bathing and hand washing as sufficient protection, a belief that likely accounts for the paradox of near-universal hygiene compliance (99.0% reported immediate hand washing) coexisting with universal DEP and DETP detection in biomonitored samples. This confirms that exposure occurs predominantly during mixing and application, before hygiene measures are applied.

THE SOCIODEMOGRAPHIC DETERMINANTS OF EXPOSURE

Pesticide exposure varied significantly across sociodemographic groups, including age, sex, marital status, education level, and farm size. Younger farmers exhibited higher exposure, which may reflect differences in risk perception and adherence to safety practices. Lower educational attainment and smaller farm size were associated with higher exposure, consistent with evidence that education influences comprehension of safety instructions and adoption of safer agricultural practices. These findings highlight the need for equity-focused interventions that address vulnerable subgroups within farming communities.

Gender-related exposure patterns were complex. Although men were primarily responsible for pesticide application, higher adjusted odds of exposure among women likely reflects involvement in secondary tasks such as mixing concentrated formulations, washing pesticide-contaminated clothing and equipment, and repurposing empty pesticide containers for domestic water storage. The complexity of these patterns was illuminated by FGD findings. While men predominated in pesticide application roles, consistent with the quantitative finding that males constituted two-thirds of the sample, female participants described regular involvement in precisely these secondary handling activities. These secondary exposure pathways, largely invisible in self-reported application data, provide a plausible explanation for the reversal in the direction of the sex odds ratio between the crude and adjusted models in Table 3, and reinforce the need to assess exposure across all household pesticide-handling roles rather than application alone. It should be noted that several subgroup categories in Table 3, including primary education and select ethnic groups, yielded wide confidence intervals due to sparse cell counts, and these estimates should be interpreted with caution.

THE POLICY AND PRACTICE IMPLICATIONS

The findings of this study have important implications for occupational and environmental health policy. First, reliance on self-reported knowledge and practices is likely to underestimate true pesticide exposure, highlighting the need to incorporate biomonitoring into surveillance systems. Second, interventions must extend beyond awareness campaigns to address structural barriers, including cost and accessibility of PPE, weak regulatory enforcement, and limited extension services. Targeted, context-specific training programmes delivered through primary healthcare systems, agricultural extension services, and farmer cooperatives are urgently needed. Subsidised or free PPE distribution, regulation of pesticide vendors, improved equipment standards, and promotion of integrated pest management (IPM) are critical to reducing exposure. National restrictions on highly hazardous pesticides and strengthened enforcement by regulatory agencies are also essential.

FGD participants consistently identified cost and market unavailability as the principal barriers to PPE use, with several describing attempts to improvise protection using ordinary clothing. This pattern was corroborated quantitatively, where only 44.5% reported consistent PPE use despite 62.0% reporting any use at all. This convergence of qualitative and quantitative evidence suggests that supply-side interventions, specifically subsidised PPE distribution through farmer cooperatives and primary healthcare facilities, are likely to yield greater reductions in exposure than awareness-based programmes alone, particularly given that knowledge level was not independently associated with biomarker concentrations in this study.

THE STRENGTHS AND LIMITATIONS

A major strength of this study is the integration of biomonitoring, quantitative survey data, and qualitative insights, providing a comprehensive mixed-methods assessment of pesticide exposure and its determinants. This is an approach that is particularly novel in the Nigerian and sub-Saharan African context where biomonitoring data remain scarce.[24] The use of GC-MS analysis of six urinary DAP metabolites, with robust quality assurance measures including matrix-matched calibration curves, procedural blanks, and internal standards, further strengthens the validity of the biomonitoring component.

However, some limitations must be acknowledged. Reliance on self-reported practices may be affected by recall or social desirability bias. The biomonitoring subsample (n=54) was relatively small due to laboratory cost constraints, and while a household-based random sampling approach was used, embedded within the same sampling frame as the parent survey to minimise systematic selection bias, no formal comparison of key sociodemographic characteristics between the 54 biomonitored participants and the 254 not biomonitored was conducted; this should be considered when interpreting the biomonitoring findings. The biomonitoring sample size is nonetheless consistent with prior organophosphate exposure studies that have demonstrated adequate exposure characterisation with samples of 40 to 60 participants.[14,15] Another limitation is the non-specificity of DAP metabolites, which do not permit identification of individual parent pesticides and may reflect dietary as well as occupational exposure. Despite these limitations, the convergence of biomonitoring, survey, and qualitative evidence across multiple data sources substantially strengthens confidence in the overall findings.

CONCLUSION

This study provides a critical evidence base on organophosphate pesticide exposure among smallholder farmers in Nigeria, moving beyond subjective self-reports to objectively quantified internal dose through urinary biomonitoring. The universal detection of dialkylphosphate (DAP) metabolites with DEP and DETP found in 100% of farmers, provides incontrovertible biochemical evidence of widespread exposure. This is a finding that starkly contrasts with the perceived safety reflected in self-reported practices. Crucially, the study also reveals a dangerous dissonance between knowledge, behavior, and exposure. While basic awareness of pesticides is high, it does not translate into protective actions, largely due to structural and socioeconomic barriers such as the cost and accessibility of Personal Protective Equipment (PPE), reliance on informal learning networks, and weak regulatory enforcement. The significant association between safe farming practices and lower biomarker levels underscores the protective value of behavior modification, while the persistence of unsafe handling as exemplified by 86% of farmers reporting dermal or ocular contact, highlights the urgent need for systemic intervention.

These findings challenge the efficacy of awareness-only campaigns. Sustainable exposure reduction will require a multi-faceted strategy that includes: (1) subsidized and accessible PPE distribution; (2) enforcement of existing regulations on highly hazardous pesticides; (3) the revitalization of agricultural extension services to deliver context-specific training; and (4) the promotion of integrated pest management (IPM) as a viable economic alternative. Furthermore, this study demonstrates the essential role of biomonitoring in occupational health surveillance. Integrating objective exposure assessment into public health practice is indispensable for accurately characterizing risk, identifying vulnerable subgroups, and evaluating the effectiveness of interventions. This research thus serves as a foundational call to action for policymakers, healthcare providers, and agricultural stakeholders in Nigeria and across sub-Saharan Africa to bridge the dangerous gap between perception and reality in pesticide safety.

DECLARATIONS

Consent to Participate: Written informed consent was obtained from all participants before they were enrolled in the study. Participation was voluntary, and confidentiality was assured.

Consent to Publish

Not applicable: No identifying information or images of individual participants are included in this manuscript.

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Clinical trial number: Not applicable

Conflict of Interest: No Conflict of Interest

Public and Patient Involvement Statement

Smallholder farmers and local community stakeholders were engaged during the planning and implementation of this study. Their input helped refine the study tools, improve the clarity of questionnaire items, and guide the focus group discussion themes to reflect real-life pesticide use practices. Community leaders and area council representatives supported participant mobilization and facilitated access to study sites. Although participants were not directly involved in the laboratory analysis or final interpretation of biomonitoring results, findings were communicated back to relevant community stakeholders and will be used to inform future farmer focused health education and pesticide safety interventions.

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