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Farmers' pesticide use, disposal behavior, and pre-harvest interval: a case study from Nigeria

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In Sub-Saharan Africa, small farmers rely heavily on synthetic pesticides, the overuse of which poses significant risks to human health, the environment, and food safety. Yet detailed empirical evidence on the knowledge and drivers of pesticide management practices remains scarce, limiting insights for policymakers and development practitioners. To address this gap, we leveraged data collected from 1,556 tomato producers in Northern Nigeria to investigate the determinants of pesticide use behavior using a sequential-exploratory mixed-method approach. We examined a broader range of pest management-related practices than prior literature, including safety equipment usage, pesticide disposal methods, and adherence to pre-harvest intervals (PHIs)−the intervals between the last pesticide application and the crop harvest. We found substantial non-compliance with the recommended practices: 45% of farmers reuse empty pesticide containers for other purposes, 14% discard them on the farm, 15% burn containers in open fires, and 40% harvest tomatoes within 1–5 days after pesticide application, violating the 7-day PHI guideline. These findings suggest that many tomato farmers adopt unsafe practices, which have adverse implications for their health, the environment, and the safety of food for consumers. We show that training on pesticide disposal and midstream market channels (e.g., wholesalers and aggregators) are strongly correlated with improved pesticide handling and PHI compliance. Overall, our results underscore the need for targeted training programs to enhance farmers' awareness of safe pesticide application, disposal practices, and PHI adherence. These efforts should be complemented by stronger regulatory frameworks and mechanisms to align farmer pesticide use practices with consumer preferences for safe products, as observed in the higher PHI adherence among farmers selling to midstream actors.

KEYWORDS

pesticides, disposal, use practices, food safety, integrated pest management, pre-harvest interval

1 Introduction

Agriculture in developing countries faces several challenges, including pest and disease infestation among other biotic, abiotic, market, and institutional factors. Severe pest infestation substantially reduces crop yields and quality, with significant negative impacts on farmers' earnings and the total agricultural output of the region. Conventional pest management approaches frequently depend on the extensive use of chemical pesticides. The utilization of such pesticides has been identified as the most straightforward and efficient approach to managing pests in vegetable cultivation (Pretty and Bharucha, 2015). However, this practice poses a significant risk to food safety, human health, the environment, and agricultural sustainability.

Farmers in low-income nations heavily depend on synthetic pesticides to control agricultural pests and diseases (Pretty and Bharucha, 2015; Schreinemachers et al., 2016). While pesticides represent a significant advancement in contemporary agriculture, misapplication may lead to the development of resistance to pests, issues of pesticide residues in crops, the contamination of soil and water, and unintended effects on non-target plants and animals (Boateng et al., 2023). Pesticides are among the leading causes of death by self-poisoning, particularly in low- and middle-income countries (WHO, 2019, as cited in Madaki et al., 2024). Aniah et al. (2021) estimated that nearly 3 million farmers suffer from severe pesticide poisoning and 25 million from mild pesticide poisoning annually, resulting in ∼180,000 deaths per year. Although developing countries use only 25% of the pesticide produced worldwide, they account for 99% of the associated deaths. This is because pesticide use tends to be intense and unsafe, and regulatory, health, and education systems are weaker in developing countries, including Nigeria. Ongoing scientific and public debates are focusing on minimizing the adverse effects of pesticide use on human health and the environment (Oyekale, 2018; Boateng et al., 2023; Madaki et al., 2024).

The tomato leaf miner (*Tuta absoluta*) also known as the South American tomato pinworm or "Tomato Ebola," is an invasive pest that significantly threatens tomato production in West Africa (Sahel, 2017). This pest's invasive nature can result in as much as 80% yield loss (Bala et al., 2019; Aigbedion-Atalor et al., 2020). As described by Bala et al. (2019), in 2016, northern Nigeria experienced a devastating infestation of tomato leaf miner, leading to soaring tomato prices across the country. Unfortunately, information on the resistance status of this pest in Nigeria is still lacking, hampering appropriate control measures. The situation remains largely unchanged, and tomato farmers continue to count their losses because of the dreaded *T. absoluta*. Farmers utilize chemical management strategies in an attempt to mitigate the detrimental effects of the disease. However, as a consequence, the occupational risks to farmers and the food safety risks to consumers increase, especially when pesticides are applied sub-optimally (Ijeoma et al., 2020; Odewale et al., 2021).

In Nigeria, the pesticide market remains largely unregulated, with most farmers buying pesticides from open markets with minimal advisory support on safe use and disposal practices (CropLife Africa Middle East, 2015; Oludoye et al., 2021; Madaki et al., 2024). This can lead to the irrational use and mismanagement of pesticide leftovers by farmers in their efforts to combat the tomato leaf miner and other pests. A recent study in five low- and middle-income countries (LMICs) revealed that pesticide residues on fruits and vegetables were consumers' most frequently cited source of food safety concerns (Tambo et al., 2024). This is particularly concerning in Nigeria, where fresh tomatoes are increasingly consumed in daily dishes (Adeoye et al., 2017). These residues therefore constitute one of the biggest threats to food safety, especially in vegetables like tomatoes. However, the lack of information regarding farmers' knowledge and perception of pesticide handling and disposal management behavior is the primary constraint in implementing a sustainable management approach that is eco-friendly and socially and environmentally compatible with smallholder diverse cropping systems (Rahman et al., 2022).

Previous studies have extensively examined the negative health and environmental impacts of pesticide use in developing countries (Oyekale, 2018; Soko, 2018; Mehmood et al., 2021; Odewale et al., 2021; Boateng et al., 2023). The role of stakeholder information in shaping pesticide handling and management practices has also been explored (see Fan et al., 2015; Jin et al., 2015; Madaki et al., 2024). However, significant gaps remain in understanding farmers' behaviors across the pesticide life cycle, including their awareness, application, disposal practices, and compliance with pre-harvest intervals (PHIs). Furthermore, few studies have employed representative mixed-method approaches that integrate qualitative and quantitative insights to comprehensively address these dimensions. This study seeks to bridge these critical knowledge gaps by examining the pesticide use behavior of tomato growers in northwest Nigeria, the country's primary horticulture-producing region and leading pesticide consumer.

This paper's contribution to the literature is twofold: first, we examine the drivers of sustainable pesticide use behavior across various components of the pesticide life cycle. Most previous studies either focus on personal protective equipment (PPE; Mehmood et al., 2021; Madaki et al., 2024) or disposal practices (Madaki et al., 2024), but we extend the literature by considering PPE, disposal practices, and compliance with PHIs. The PHI is the mandated waiting period between the final pesticide application and the crop harvest, ensuring that any pesticide residues on the crop have depleted to safe levels, making the produce safe for human consumption according to regulatory standards. Typically indicated on pesticide labels, PHIs guide farmers on the safe timing for harvest after application and vary depending on the specific pesticide used, crop type, and environmental conditions. Despite compliance with PHIs being critical for ensuring food safety and public health, it has been largely overlooked in the existing literature, particularly in the African context, where regulatory enforcement is weak and farmer awareness is limited. We argue that since smallholder farmers are the primary actors in agricultural supply chains in developing countries, their pesticide use practices affect not only them but also consumers through food residues. Addressing these practices requires a systemic perspective encompassing pesticide use, disposal, and adherence to food safety behaviors to design context-specific agri-environmental and food safety policies.

Second, we use a sequential-exploratory mixed-method approach to provide insights into the behavioral determinants of safe pesticide use and the management practices of farmers. Most existing studies predominantly rely on quantitative methods, such as cross-sectional surveys (see, Oyekale, 2018; Mehmood et al., 2021; Odewale et al., 2021; Madaki et al., 2024), which often fail to capture farmers' internalized perceptions and intuitions about pesticide use (Abadi, 2018). In contrast, the mixed-method approach, which combines qualitative and quantitative data, enables a more nuanced understanding of these behaviors. To our knowledge, only two studies—Abadi (2018) in Iran and Boateng et al. (2023) in Ghana—have applied this design to examine pesticide use behaviors. However, we build on these two studies using a more recent dataset, a different cropping context, and an estimation strategy that captures the interdependence of pesticide life cycle components.

Evidence indicates that over 200,000 deaths occur annually in Nigeria due to polluted food, making farmers' pesticide use behavior and compliance with PHIs in Nigerian agriculture worth investigating (Onyeaka et al., 2021). Studies also suggest that pesticide residue levels in fresh vegetables and fruits in Nigeria often exceed acceptable standards (Ibrahim et al., 2018; Omeje et al., 2022; Oyinloye et al., 2021). For instance, Omeje et al. (2022) reported 38 pesticide residues in selected fruits and vegetables in the country, highlighting significant health risks from their consumption. The increasing trend in pesticide use in Nigeria necessitates routine monitoring of pesticide management practices and residues in agricultural produce to ensure consumer safety.

This study's findings provide valuable insights for policymakers and agricultural extension services, guiding initiatives to promote sustainable pesticide adoption and management techniques that ensure food safety while protecting environmental and public health in Nigeria, the largest importer of pesticide in Africa. Additionally, this study contributes to the literature on sustainable agriculture, food safety, and public health in sub-Saharan Africa and the Global South, addressing a pressing issue at the intersection of food systems, health, and environmental sustainability.

The sections of this paper are organized as follows: Section 2 reviews the trends in the Nigerian pesticide sub-sector. Section 3 presents the theoretical framework derived from the literature on the behavioral determinants influencing smallholder farmers' pesticide use in the Global South. Sections 4 and 5 outline the data collection procedures and the estimation strategy the study employs. Section 6 presents and discusses the findings, divided into two subsections: the first focuses on the qualitative results and the second on the quantitative findings, including the behavioral determinants of pesticide use. We close with the conclusions, a discussion of policy implications, and suggestions for future research.

2 Pesticide sector development in Nigeria

The pesticide sector in Nigeria has a long history of dominant pesticide importation from developed countries. Nigeria accounts for more than a quarter of the share of total pesticides used in Africa, and their utilization in the agricultural sector has grown by 70%, from 33,968 tons in 2012 to 57,822 tons in 2022 (Figure 1A). Insecticides, herbicides, and fungicides are the major pesticides used in the country. The use rate of these pesticides for weed control and crop protection has doubled in the last 10 years due to several factors.

Figure 1B illustrates the increasing pesticide use intensity in Nigeria relative to other parts of Africa from 1990 to 2022. The graph reveals that Nigeria's pesticide use intensity was less than half of Africa's average in the early 1990s, intermittently rising and falling between 1996 and 2008 while remaining lower that of most other African countries. However, since 2010, the intensity of pesticide use in Nigeria has been significantly higher than that of other African countries, with use rates in 2022 triple those in 2010 and more than double those of the continent as a whole.

Before the 1998 Koko port incident, when 4,000 tons of toxic waste was dumped by an Italian company, Nigeria had no concrete environmental policy or framework (SEDI, 2021). Since then, several decrees and policies have been enacted, and agencies have been constituted to oversee the challenges affecting health and the environment, including the Federal Environmental Protection Agency (FEPA), Federal Ministry of Health and Social Welfare (FMOH and SW), National Environmental Standards Regulatory

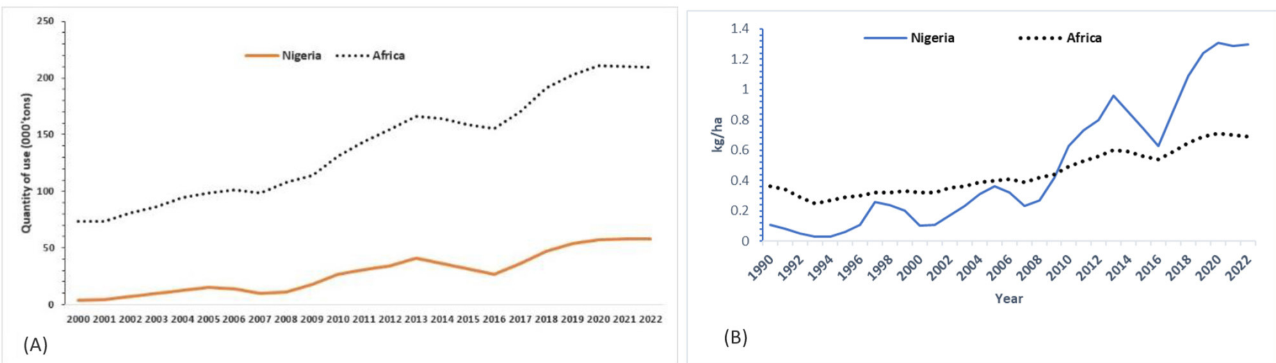

FIGURE 1
(A) Pesticides use in Nigeria and Africa from 1990 to 2022. Source: FAO (2024). **(B)** Pesticides use intensity in Nigeria and Africa 1990–2022.

and Enforcement Agency (NESREA), and National Agency for Food and Drug Administration and Control (NAFDAC). Nigeria has also been party to several international treaties and conventions on issues pertaining to human health and environmental sustainability, including the Stockholm Convention, the Rotterdam Convention, the Basel Convention, The Montreal Protocol, the Bamako Convention on Hazardous Wastes, and the International Code of Conduct on Pesticides Management (SEDI, 2021).

Despite all these efforts, Nigeria remains faced with public health and environmental challenges due to high levels of pesticide use and poor pesticide education, aside from being the highest importer in Africa (Oluwole and Cheke, 2009; SEDI, 2021; Pesticide Atlas, 2022). The inadequate regulatory framework for pesticide use and management has led to the high importation of unregistered and banned pesticides, as most of those used mainly by small-scale farmers are hazardous (Omohwovo et al., 2024). According to Pesticide Atlas (2022), more than 50% of these pesticides are no longer authorized in the European Union market due to their harmful effects on the environment and health. Some highly hazardous pesticides are still registered in Nigeria, and some that have been banned in other countries are still available at agrochemical stores. The lack of adequate and robust laboratories and personnel for testing is one of the critical challenges affecting pesticide management (Omohwovo et al., 2024).

3 Farmer pesticide decision-making and behavioral determinants in the global south

We present a conceptual framework that outlines the decision-making processes of smallholder farmers exposed to pesticides and their adoption of averting behaviors to mitigate their adverse effects on health and the environmental risks. This framework is based on utility maximization theory, which posits that farming households' decisions about input demand and subsequent output supply are determined by agroecological considerations, market conditions, and household characteristics (including farmer knowledge and assets), and provides insights into the determinants of safe pesticide practices in the Global South.

In the Global South, small-scale farmers are often exposed to high pesticide levels due to climatic conditions, pesticide overuse, and a lack of awareness about using protective equipment (Abadi, 2018; Akter et al., 2018). Although pesticides can contribute to the productivity of small-scale farms, they also threaten environmental ecosystems and human health (Bonner and Alavanja, 2017; Hayes and Hansen, 2017; Deknock et al., 2019). While countries in the Global North continue to make pesticide regulations more stringent, most countries in the Global South do not have the capacity for residue testing (Dinham, 2003). Small-scale farms operate as family businesses where the farmers themselves spray their crops, whereas large-scale farms employ farm workers and specially trained sprayers to apply the pesticide (Ruth and Jennifer, 2023).

Following Mehmood et al. (2021), we analyzed the conditioning factors influencing farmers' decisions to use safe pesticide handling and management practices using the conventional averting behavior model. Averting behavior refers to actions taken to defend against environmental or other hazards, whether by reducing exposure to hazards or by mitigating the adverse effects of exposure (Dickie, 2017). A rational household facing pesticide exposure will act to defend itself if it perceives the benefits of defensive action to be greater than the costs. In our context, aside from avoiding exposure, growers are assumed to take actions to offset pesticide externalities by using PPE during pesticide application, practicing safe disposal methods for pesticide containers, and adhering to essential harvest intervals to reduce pesticide residue on crops.

$$U = U\left(x,\ h\right), \tag{1}$$

where x in Equation 1 represents, the consumption of goods derived from income from farming outputs (e.g., tomato sales). Farmers' health (h) is influenced negatively by pesticide exposure but improved by averting behaviors.

$$h = f\left(I,\ q\right), \tag{2}$$

where I in Equation 2 represents averting behavior (e.g., use of PPE, proper disposal, adherence to PHIs) and q denotes environmental quality resulting from pesticide residues in soil, water, and crops, influenced by broader pesticide management practices. Growers can offset the effect of pesticide externalities by using more I. However, farmers face a trade-off between maximizing income and investing in averting behavior.

$$y = x + pI, \tag{3}$$

where y in Equation 3 represents total income, x the consumption of goods, and pI the cost of averting inputs. Thus, farmers choose the level of averting behavior that maximizes utility subject to their budget constraints. Following Dickie (2017), we can rewrite the Lagrange function as follows in Equation 4:

$$L\ (x,\ I,\ \lambda) = U\left[x, f\left(I,\ q\right)\right] + \lambda\left[y - x - pI\right], \tag{4}$$

The first-order condition (FOC) for optimal averting behavior is given in Equation 5:

$$\frac{\frac{\partial U}{\partial h}}{\frac{\partial U}{\partial x}} = \frac{p}{\frac{\partial f}{\partial I}}, \tag{5}$$

From the FOC, we can obtain the reduced form of a Marshallian demand function for averting behaviors to analyze factors influencing the adoption of safe pesticide management practices,

$$I_j^* = \beta_{j0} + \sum_{k=1}^{n} \beta_{jk} X_k + \epsilon_j \ \left(j = 1,\ 2,\ \ldots..,\ n\right), \tag{6}$$

where j indexes the averting behavior, X in Equation 6 denotes farmer characteristics and institutional factors, and $\in$ is the error term.

Empirical literature about the Global South provides various explanations for growers' pesticide management and handling practices. We group these explanations into the following four categories. (1) *Household and farm characteristics*. Risk aversion positively correlates with household age and education (Jin et al., 2015). We, therefore, hypothesized that older and more educated farmers are more likely to use personal safety equipment, adequately manage pesticide waste disposal, and adhere to waiting periods. In line with Mehmood et al. (2021), who found that households with young children are more concerned about health-related issues, it was assumed that the number of small children in the household might encourage the adoption of safer pesticide-handling practices (Mehmood et al., 2021). Furthermore, the scale of the farm matters (Jin et al., 2015). Okoffo et al. (2016) reported that large-scale farmers are more likely to wear PPE during pesticide application. (2) *Pesticide knowledge*. The results of research in Iran indicate that pesticide knowledge is positively associated with pesticide use behavior (Abadi, 2018). Pesticide knowledge positively correlates with the ability to read and comprehend instructions, including pesticide labels, safety guidelines, and recommendations (Atreya, 2007). Awareness can improve farmers' capacity to critically evaluate pesticides' human and environmental risks and benefits and follow best practices (Abadi, 2018). On the other hand, Guivant (2003) argues that advice from training officers may inadvertently encourage farmers to use pesticides in a preventive manner. As a result, farmers might disregard the rest period after pesticide application, thus increasing the risks of residue consumption. Knowledge of integrated pest management (IPM) contributes to reducing pesticide use (Dinham, 2003; Mehmood et al., 2021). In this study, we hypothesize that farmers who receive training about the principles of pesticide use, pest management, and pesticide disposal can control pests and diseases efficiently by applying IPM, which can affect their level of pesticide use, disposal management, and PHI adherence. (3) *Institutional factors*. Access to extension services was assumed to encourage the adoption of better pesticide-handling practices (Mehmood et al., 2021). (4) *Market channel*. Dinham (2003) observed that small-scale farmers often struggle to meet the increasing quality standards and traceability requirements of lucrative markets due to inadequate pesticide management practices and improper application rates. However, in many developing countries, vegetable producers primarily supply traditional markets without formal contracts. As a result, the impact on pesticide management practices of selling to midstream actors remains largely uncertain.

4 Study area and sampling technique

The study was conducted in Kano state in northwest Nigeria (Figure 2). Kano state is Nigeria's highest pesticide user state, in which 396,000 farmers have reported using pesticides (NBS, 2012). This study used cross-sectional survey data from 1680 tomato farmers across four Local Government Areas (LGAs) with the highest tomato production in Kano State. The study sample was selected using a multi-stage sampling approach. First, the four LGAs with the highest potential for tomato production were selected—Bichi, Bunkure, Karaye, and Garun Mallam. Subsequently, from the list of tomato-growing communities, 84 were randomly selected. To account for differences in the size of each LGA, the community selection was proportionate to the size of tomato producers. In each community, ∼20 farmers were randomly selected who had grown tomatoes for at least two consecutive seasons in the last 2 years, resulting in 1,680 farmers. Random selection from the producer listing exercise was conducted using a research randomizer following Urbanika (2013). Data were collected between June and July 2023. Given the study's focus on the appropriate use of pesticides and pesticide equipment, we restricted the analysis to households that use pesticides. This left us with a final sample of 1,556 households, 91% of the original sample.

A face-to-face interview was designed to collect data on farmers' knowledge, attitudes, and practices regarding pesticide use and disposal practices. A structured questionnaire was developed by considering the local context and language. The questionnaire was also designed based on relevant studies in the research area in developing countries (e.g., Mengistie et al., 2017; Mubushar et al., 2019; Mehmood et al., 2021; Madaki et al., 2024). The questionnaire was pre-tested to ensure clarity and comprehensibility. Primary data were also augmented with focus group discussions from a randomly selected group of 90 tomato farmers from eight villages in the four LGAs in Kano state. The eight villages were Bunkure and Lautai from Bunkure LGA, Yola and Mallam Sani from Karaye LGA, Dorowa Sallau and Dumaje from Garun Mallam LGA, and Sabo Bichi and Yakassai from Bichi LGA. The focus group discussions were conducted with the assistance of local extension officers in the villages. The structure of the discussion with respondents in the focus group was related to their knowledge and opinions about pest and disease management and pesticide use and types. It also included efforts to gage farmer understanding of pictogram, PPE usage, knowledge about PHI, training exposure, access to pesticides-related information, utilization of spray service providers (SSPs), and adverse effects of pesticides on humans, livestock, and the environment, among others. A laminated picture of a pictogram was used to measure farmers' knowledge of the interpretation of the toxicological band on the pesticide label.

5 Estimation method

We empirically analyzed the safe pesticide handling and management practices of growers by dividing them into three stages: (i) PPE use, (ii) safe disposal behavior, and (iii) adherence to PHIs. The use of PPE was measured by asking farmers how frequently they used four types of PPE: personal protective clothing, masks, goggles, and rubber boots. For each PPE type, separate binary variables were constructed to indicate whether farmers regularly used the specific equipment. For safe disposal behavior, we categorized pesticide container disposal methods into two types based on the study context and predominant practices: 1) acceptable practices, i.e., giving back containers to spray service providers and burying pesticide containers, and 2) unacceptable practices, i.e., burning; throwing pesticide containers into a field, bushes, waste dumps or waterways; selling to hawkers; or reusing them for other purposes. Although all these disposal methods are associated with some hazardous effects on humans and the environment, we considered those farmers who used acceptable

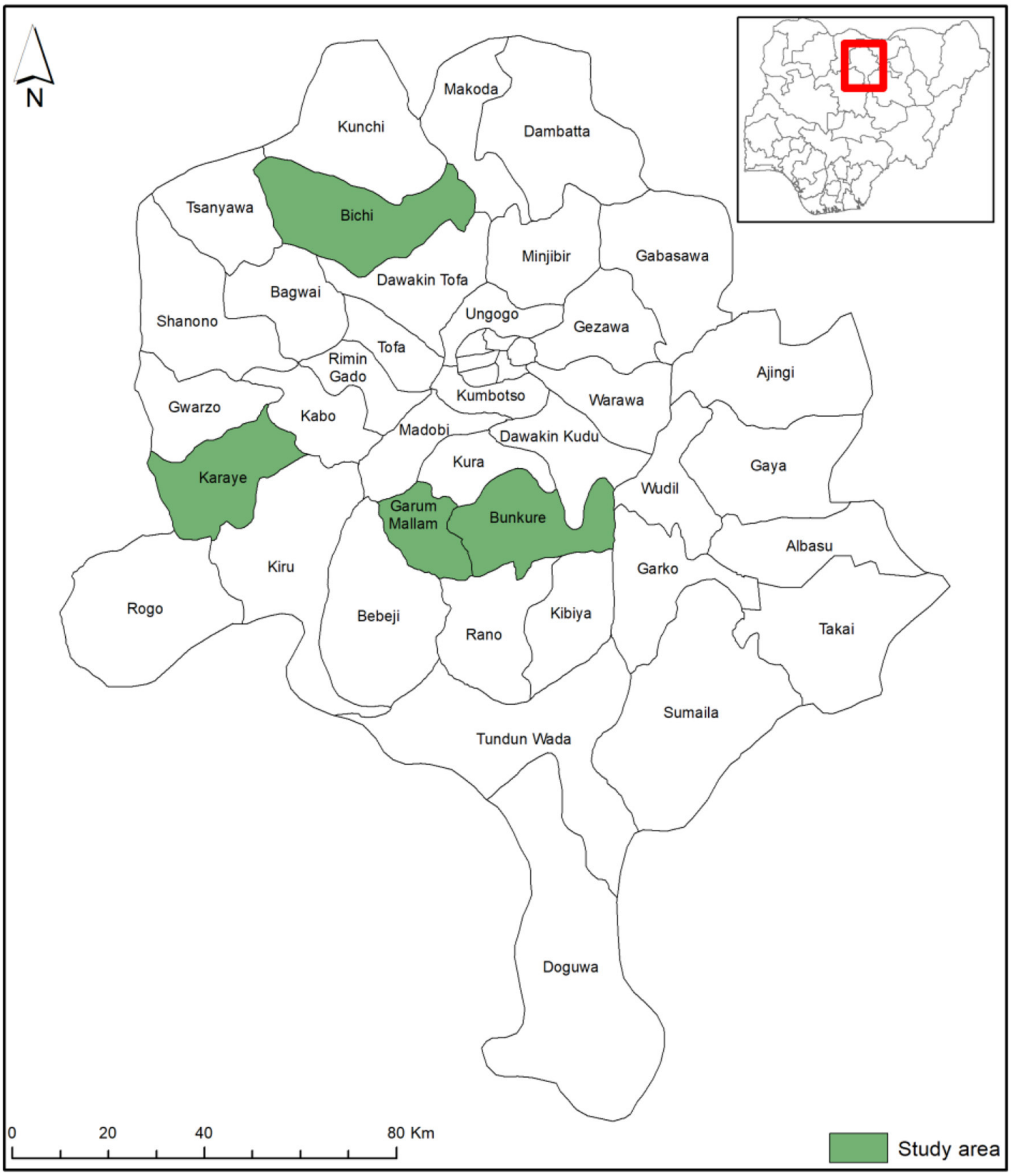

FIGURE 2
Map of Nigeria and the four local governments in Kano state.

practices to be adopters of less hazardous disposal methods and assumed they have better awareness about pesticides' health and environmental risks and the disposal of containers in the absence of a collection system for their recycling or incineration in the study areas. The dependent variable in the second model was binary, i.e., farmers using the acceptable practices for the disposal of pesticide containers were assigned one and those using unacceptable practices zero, as implemented by Mehmood et al. (2021).

PHI was measured based on the waiting periods adopted by farmers after pesticide application, considering the major active ingredients used in the study area gathered from the focus group discussions. Farmers extensively use three active ingredients: Lambda cyhalothrin, profenofos + cypermethrin, and Imidacloprid. Thus, a short PHI after pesticide application—in this case, $<$7 days—was considered a concern for pesticide residue and was modeled as zero, and farmers who harvested 1 week after pesticide application were modeled as one.

This study used a multivariate model, which allows for the joint estimation of the factors affecting the adoption of safe pesticide use, disposal practices, and compliance with PHIs (Greene, 2012). Overlooking such interdependence and concurrent adoption decisions may result in biased estimates (Kiefer, 1982). Assuming that these practices are simultaneous adoption decisions, our model can be written as follows:

$$\mathbf{Y_{ij}} = \mathbf{x}_{\mathbf{ij}}^{'}\beta_{\mathbf{j}} + \varepsilon_{\mathbf{ij}}, \tag{7}$$

where Y_{ij} $(j = 1, \ldots..m)$ represents the latent binary variables denoting the adoption of the jth stage of practices, where there are m stages, faced by the ith tomato growers. $x_{ij}^{'}$ is a 1x k vector of independent factors affecting the adoption of safe pesticide handling and management, β_j is a k x 1 vector of parameters to be estimated, and ε_{ij} is the unobserved error term. Hence, **Equation 1** will have a system of three equations:

$$\mathbf{Y}_1^* = \alpha_1 + \mathbf{X}_1\beta_1 + \epsilon_1, \tag{8}$$
$$\mathbf{Y}_2^* = \alpha_2 + \mathbf{X}_2\beta_2 + \epsilon_2, \tag{9}$$
$$\mathbf{Y}_3^* = \alpha_3 + \mathbf{X}_3\beta_3 + \epsilon_3, \tag{10}$$

where Y_1^* = model 1 (PPE use), Y_2^* = model 2 (pesticide disposal), and Y_3^* = model 3 (pre-harvest interval), ϵ_{im} are multivariate normal distributed error terms with a mean of zero (Cappellari and Jenkins, 2003). To increase model accuracy, we adjusted the random draw to 50 by approximating the square roots of the valid observations (Cappellari and Jenkins, 2003, as cited in Kotu et al., 2017). A variance inflation factor (VIF) was estimated to check the presence of multicollinearity, and all the explanatory variables had a VIF <3 with a mean VIF value of 2.88, indicating that a perfect linear relationship between explanatory variables is not an issue in our model. In addition, robust standard errors were reported to correct for possible heteroscedasticity. Since some covariates might be endogenous, our results should be interpreted as correlations rather than causal relationships.

5.1 Variable definition and descriptive statistics

The covariates included age, training in good agricultural practices and pesticide disposal, education level, number of children, farm size, extension access, membership of farmers' associations, and source from which pesticides were purchased. The choice of these explanatory variables was informed by the theory of averting behavior and literature on farmers' pesticide handling and management practices in developing countries (Okoffo et al., 2016; Mubushar et al., 2019; Mehmood et al., 2021; Boateng et al., 2023). The definition and descriptive statistics of all explanatory variables are summarized in Table 1. We also considered other factors that were not taken into account in previous research but that may affect growers' choices regarding safe pesticide handling and management practices, such as selling to midstream value chain actors and community access to SSPs.

TABLE 1 Definition and summary statistics of the variables used in the analysis.

Variable name	Variable definition	Mean	SD
Age	Age of the household head (years)	42.674	11.36
Training	Training index of good agricultural practices and training received in the last 5 years	0.158	0.335
Training disposal	Whether a farmer receives pesticides training disposal (yes/no)	0.265	0.442
Extension access	Access to public extension services (yes/no)	0.201	0.401
Education	Received formal education (yes/no)	0.644	0.479
Sprayer service provider (SSP)	Access to community SSP (1 if the community has local SSP provider, 0 otherwise)	0.715	0.451
Farm size	Tomato farm size (hectare)	0.903	0.655
Kids	Number of children in school	4.267	3.054
Farmers association	Membership of a farmers' association (yes/no)	0.214	0.41
Open market	Pesticide purchase from open market (yes/no)	0.352	0.478
Agro-dealers	Pesticide purchase from agro-dealers (yes/no)	0.628	0.484
Wholesaler *(base = retailers)*	Selling to wholesalers (yes/no)	0.658	0.475
Aggregator *(base = retailers)*	Selling to aggregators (yes/no)	0.268	0.443

The descriptive analysis revealed that the average household head was 43 years old, and 64% of them had received formal education. The surveyed households cultivated on average 0.9 hectares of tomatoes and had more than four children. Access to agricultural training was limited, with only 16% of farmers reporting having received training on good agricultural practices in the past 5 years, and 26% having received specific training on pesticide disposal. Additionally, 20% of households had access to public extension services, highlighting gaps in agricultural support services. About 72% of the community had access to local SSPs. Regarding marketing practices, the majority of farmers sold their produce to midstream actors, such as wholesalers and aggregators, rather than directly to retailers.

6 Results and discussion

6.1 Focus group discussion results

This section presents the key findings of the focus group discussion about major tomato pests and diseases, common pesticide types used by farmers, and growers' perceptions of pesticide usage.

6.2 Pest prevalence and farmers perception of crop damage

An analysis of the major tomato pests and diseases in the region shows that tomato leaf miner (*T. absoluta)* is the most widespread and dreaded threat to tomato production in the region both in terms of farmer perception and actual damage (Figure 3). About 87% of participating farmers considered *T. absoluta* the biggest threat to their farms, followed by bollworms and post-transplant diseases (Figure 2). More than 80% of farmers also mentioned that *T. absoluta* caused 80–100% yield losses (Figure 2)[1]. *T. absoluta* was first reported in the Kadawa irrigation valley of Kano state in 2015. Ever since, it has become widespread and well-known all over Nigeria due to its devastating effects, especially in the Northern and Middle-belt parts, which are the major tomato producing regions. The damage caused by *T. absoluta* was so catastrophic that it led to a massive scarcity of tomatoes across the country. The tomato price skyrocketed by over 130% because of tomato leaf miner[2] due to the extreme difficulty in managing and controlling the pest.

6.3 Pesticide use and type

Table 2 presents 35 different pesticides reportedly used by farmers in the eight villages. The majority of the farmers resorted to the use of synthetic pesticides with the following active ingredients: Lambda cyhalothrin (80%), profenofos + cypermethrin (79%), Imidacloprid (88%), and 48% use DDVP (Dichlorvos) while 17% use Methomyl. These are all synthetic pesticides with various toxicity levels according to the World Health Organization (WHO) classification. Most are rated under class II, which categorizes them as moderately hazardous chemicals (WHO, 2019). However, DDVP and Methomyl are classified as highly hazardous pesticides (WHO class I) due to their presenting extremely high levels of hazards to health or environment.

At the time of the survey, Methomyl was set to be banned in the Nigerian market by NAFDAC in order to minimize the exposure of humans/animals and the environment to extremely hazardous chemicals. It has been well documented that smallholder farmers in developing countries use large amounts of pesticides belonging to classes Ia, Ib, and II due to these being cheaper than the newer, less hazardous ones (Mehmood et al., 2021; SEDI, 2021; Boateng et al., 2023). Approximately 12% of the farmers used Bacillus thuringienses (Bt), which is an IPM biological control method. Bacillus thuringienses is a gram-positive, soil-dwelling bacterium, which is lethal against several insects such as Lepidopthera (butterflies and moths), Diptera (flies), and coleoptera (beetles). It is most effective when applied at the larvae or early stages of pest development. Around 2% of growers reported having used an active ingredient that was unknown or unapproved. This is lower than that reported for other countries. For instance, Boateng et al. (2023) reported that 9.9% of cocoa farmers in Ghana were using unknown or unapproved insecticide active ingredients.

6.3.1 Farmers' awareness and perception of pesticide use

The majority of farmers obtained information on the safe use of pesticides from agro-dealers, non-governmental organizations (NGOs), extension workers, and radio (Figure 4). In addition, a significantly higher proportion of farmers reported that agro-dealers have the most influence on their decision-making regarding the choice of pesticide to buy. Agro-dealers and other farmers take the lead in terms of educating farmers about illegal/banned pesticides. Oludoye et al. (2021) stated that pesticide safety

1 While insect pests certainly pose challenges, fungal and bacterial diseases are often the primary factors limiting tomato production in Nigeria. Like most horticultural crops, tomato production is significantly constrained by diseases that reduce yield and quality. In the study area, 53% of farmers identified Bacterial Wilt as the predominant disease affecting tomato cultivation. Bacterial wilt is a serious problem in many tomato-growing areas of Nigeria, particularly in warmer regions. This usually leads to the drying of transplanted plants. According to a report by Elphinstone (2022), Bacterial Wilt can cause yield losses of up to 80% in tropical tomato-growing regions, particularly where soils remain warm and moist.

2 Why price of Tomatoes surged by 130 per cent—Nigerian govt—Daily Post Nigeria

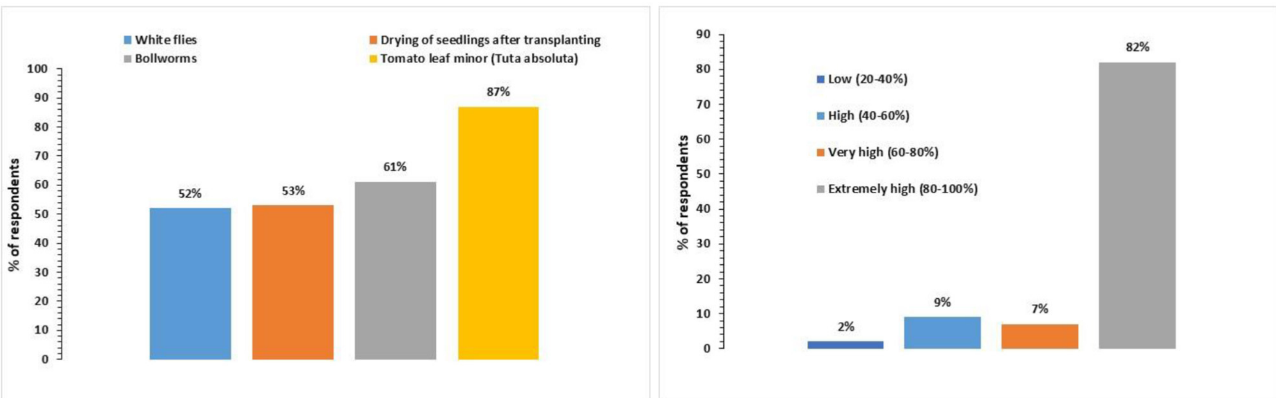

FIGURE 3
Major tomato pests **(left)** and farmers' perceptions of the degree of damage caused by *T. absoluta* (%), **(right)**.

TABLE 2 Common pesticides used by farmers in the study area.

Brand name	Product type	Active ingredients	Who toxicity class[a]	Percentage use[b]
Sharp shooter	Insecticide	Profenofos + Cypermethrin	II	79
Lara force	Insecticide	Lambda cyhalothrin	II	80
Magic force	Insecticide	Lambda Cyhalothrin + Dimethoate	II	1
Magic force gold	Insecticide	Lambda cyhalothrin + dimethoate	II	23
Cyper force	Insecticide	Cypermethrin	II	13
Caiman	Insecticide	Emamectin benzoate	III	11
Dime force	Insecticide	Dimethoate	II	1
Imiforce	Insecticide	Imidacloprid	II	88
Laraforce gold	Insecticide	Lambda cyhalothrin	II	68
Punch	Insecticide	Lambda cyhalothrin	II	12
DD Force	Insecticide	DDVP	Ib	48
Delta Force	Insecticide	Deltamethrin	II	12
Caterpillar Force	Insecticide	Emamectin benzoate	III	81
Strong Force	Insecticide	Methomyl	I	17
Aceta Force	Insecticide	Acetamiprid	U	22
Dual Force	Insecticide	Thiamethoxam + pymethroxin	III	6
Iron Force	Molluscicide	Iron phosphate	U	1
Eco Neem	Insecticide/ biopesticide	Bacillus thurengienses	N/A (Biological control)	12
V-Power	Insecticide/ biopesticide	Bacillus thuringiensis	N/A (Biological control)	22
Storm Force	Insecticide	Imidaclopríd + beta-cyflurthrin	II	2
Tuta Force	Insecticide	Chlorfenapyr	II	6
Zero force	Fungicide	Mancozeb	U	1
Best	Insecticide	Cypermethrin	II	22
Crush	Insecticide	DDVP (Dichlorvos)	?b	1
Tihan	Insecticide	Spirotetramat + flubendiamide	U	56
Indocel	Insecticide	Mancozeb	U	11
Coragen	Insecticide	Chlorantranipole	U	33
Ampligo	Insecticide	Chlorantranipole + lambda cyhalothrin	II	11
Attack	Insecticide	Lambda cyhalothrin + chlorantranipole	II	6
Duduall	Insecticide	Chlorpyrifos + cypermethrin	II	3
Y-Force	Unknown/ unapproved	Unknown/ unapproved	II	2

[a]Ib, Highly hazardous; II, Moderately hazardous; III, Slightly hazardous; U, Unlikely to pose an acute hazard with normal use.
[b]Farmers reported the use of more than one pesticide.

information provided by pesticide agro-dealers/retailers was found to be inadequate due to their interest in making profit rather than focusing on human health and the environment. Additionally, most retailers had no understanding of the characteristics of the products they sold, as they could not read pesticide labels. Schreinemachers et al. (2017) found that local knowledge-sharing has improved farmers knowledge and reduced pesticide use in Southeast Asia.

Conversely, Madaki et al. (2024) highlighted that relying on prior knowledge and information provided by other farmers to make pesticide use decisions is a serious problem because knowledge about pesticides is dynamic, especially concerning the issue of those that are banned. Since knowledge is constantly evolving with changing regulations and new scientific discoveries on pesticide efficacy and their effects on humans and the environment, decisions based solely on farmers' knowledge may become outdated. Boateng et al. (2023) noted that farmers who belong to cooperatives are more likely to be better endowed with pesticide information because they have access to training and inputs. However, despite the strong presence of tomato growers' associations and cooperatives in our study area, the role of these entities in providing pesticide use information for their members was limited.

Table 3 illustrates farmers' general knowledge of pesticide use and its harmful effects on humans, the environment, and livestock. The overwhelming proportion of farmers (87%) revealed that they are aware that pesticide use can increase farm profit. Surprisingly, 53% of farmers mentioned that using IPM is less effective than using chemical pesticides. Concerning the application and effectiveness of pesticides, more than 40% of the respondents revealed that they mix pesticides during the application to improve efficacy, which aligns with other findings in Ethiopia (Mengistie et al., 2017) and Ghana (Boateng et al., 2023). Additionally, 70% of farmers prefer to use multi-purpose pesticides that kill all insects at once, posing a risk to untargeted species. Interestingly, while 80% of farmers know that pesticides are harmful to humans, 3% said they sometimes use their teeth to open pesticide packages/containers.

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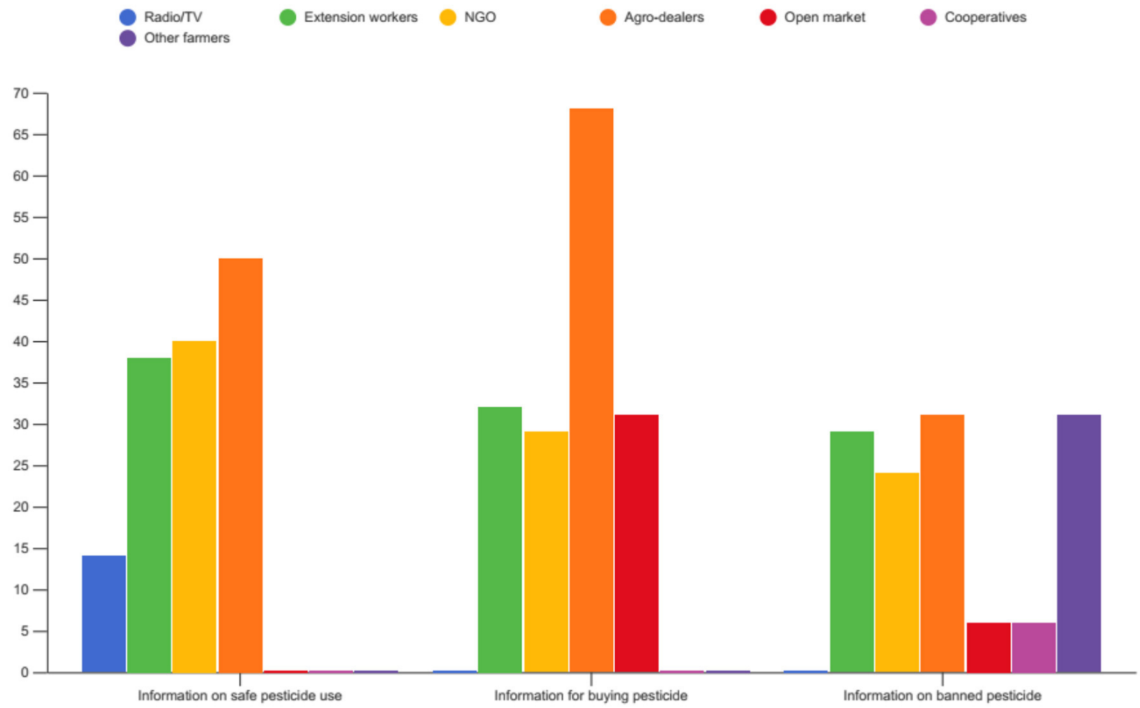

FIGURE 4
Sources of information on pesticide use, purchase, and bans (percentage).

One-third of the focus group participants (>30%) indicated that they have observed the adverse effects of improper pesticide application on sprayers. More than half of the respondents (59%) demonstrated that they were aware of the harmful effects of pesticides on livestock. In addition, a significantly high proportion (77%) of the respondents indicated their awareness of the possible contamination of the environment with pesticide residues. With respect to assessing their knowledge of the harmful effect of pesticides on consumption, 32% of farmers were worried about getting sick from consuming tomatoes from their farms due to pesticide residue issues.

6.4 Knowledge of pesticide labels

Pesticide labels provide critical information about application dosage, storage, and disposal practices. However, most farmers do not usually read or understand the labels because the language is technical, or the labels are written in a foreign language in the case of unregulated markets. During our field visits to pesticide retail shops in the study areas, we encountered labels with tiny fonts, making it difficult for farmers to understand the instructions. In addition, pesticide labels have an image explanation for safe use, safety precautions, and how dangerous the chemical is. Table 4 depicts eight of the pictographs most commonly seen on pesticide labels. Although many farmers stated that they have good knowledge of the negative effects of pesticide usage on the environment and aquatic animals, more than half of them could not recognize a pictogram indicating harm to livestock and marine animals. In contrast, the farmers were generally better able to recognize pictograms related to PPE such as gloves (89%), overalls (69%), and boots (62%). In line with Mengistie et al. (2017), most farmers lacked adequate knowledge about pesticide storage safety and potential environmental hazards, with only 3.3% of farmers understanding the pictogram indicating "keep in a safe place out of reach of children." This suggests that the pesticide information farmers receive during the purchase of the product is not very effective, especially in terms of informing them about the unintended effects of pesticides on the environment and water bodies.

Figure 5 shows that farmers store pesticides in different locations before application. Approximately 18% of the interviewed farmers stored their pesticides on the farm and 13% stored them in their living room. More than half of the focus group participants (56%) mentioned having a particular pesticide storage area. This practice is higher among our respondents than what has been reported elsewhere in Africa. In Ghana, Boateng et al. (2023) found that only 8% of cocoa farmers had a particular storage area for pesticides. However, it is very concerning to note that 22% of the farmers in our study kept their pesticides alongside foodstuff. This is consistent with previous studies in Nigeria showing that 46% of farmers stored pesticides in refrigerators with other food (Madaki et al., 2024). This practice may indicate poor adherence to pesticide safety regulations or lack of awareness among farmers about proper pesticide storage and can lead to poisoning, long-term illnesses like cancer, or developmental problems, especially for children and pregnant women.

TABLE 3 Farmers' pesticide use knowledge (%).

Pesticide awareness questions	Total ($n = 90$)	(%)[a]
Do you think the use of pesticides increases farm profit?	78	87
Mixing different pesticides can make them more effective	37	41
I prefer using pesticides that kill all insects immediately	63	70
I am satisfied with the level of control offered by chemical pesticides	49	54
Pesticides can enter the body through the skin	72	80
It is okay to reuse empty pesticide containers for other purposes	40	44
Sometimes, I use my mouth to open a pesticide package or bottle	3	3
IPM is not as effective as chemical pesticides	48	53
I am worried about people getting sick because of pesticide spraying	29	32
I am worried about pesticide residues when eating vegetables from my farm	17	19
Do you think that pesticides affect livestock?	53	59
Do you think that pesticides affect the environment?	69	77

[a]Answer options, Yes, No.

TABLE 4 Farmers' understanding of pesticide labels.

Pictogram	Meaning	I know the meaning (%)	I do not know the meaning (%)
	Keep it in a safe place out of reach of children	3.3	96.7
	Protect your feet/wear boots	62.2	37.8
	Wear protective clothing/apron	68.9	31.1
	Wear gloves	88.9	11.1
	Harmful to livestock	10.0	90.0
	Harmful to aquatic animals/fish	45.6	54.4
	Cover face	80.0	20.0
	Wash hands after use	47.8	52.2

6.4.1 Pre-harvest interval (PHI) awareness

Our results revealed that 83% of the farmers did not know the meaning of PHI, with only 17% understanding the term (Table 5). This gap in knowledge means they do not understand the importance of waiting after pesticide application before harvesting their crops. Further analysis also indicates that 97% of farmers harvest randomly without observing any specific waiting period. This practice significantly increases the risk of pesticide residues on the harvested tomatoes.

6.5 Quantitative results from survey data

6.5.1 Pesticide sources

Table 6 presents the sources of pesticides for tomato growers in Nigeria and reveals several key insights about the distribution channels through which farmers obtain them. In Nigeria, the agricultural input market is mainly privatized, and it is not surprising that most tomato growers (63%) purchase pesticides from agro-dealers. While the government and cooperative channels exist, the privatized nature of the market gives agro-dealers a larger market share. Most pesticide companies have agents who supply their products on their behalf. Agro-dealers typically build strong relationships with local farmers; most have also practiced farming in their community and become trusted sources. Trust in these dealers plays a significant role in decision-making about pesticide purchases, even though the products they supply are sometimes substandard. Open markets also represent another large share of pesticide purchases for farmers (35%), and may offer competitive prices compared to more formalized channels. For smallholder farmers, who make up the majority of tomato growers in Nigeria, cost is often a critical factor in input purchases. While open markets could provide a cheaper alternative, they are often associated with the sale of substandard or counterfeit products, which pose risks to crop safety, human health, and the environment. The Federal Ministry of Agriculture and Rural Development (FMARD) and extension agents contribute only a small fraction of the pesticide supply to farmers. The prevalence of counterfeit pesticide products in the market was raised as a significant challenge by farmers (70%), although our study did not confirm which source contributed to this. Despite cooperatives being well-positioned to provide access

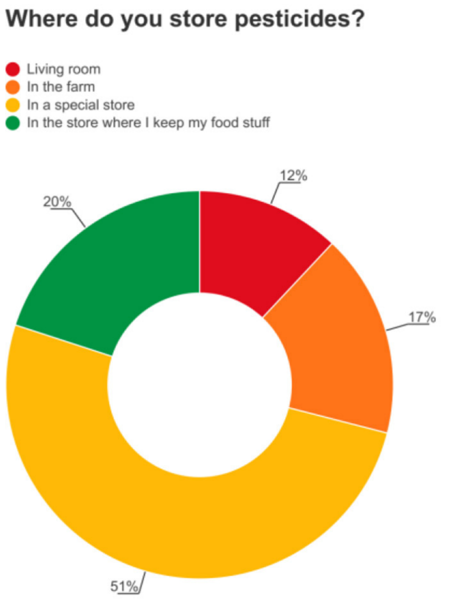

FIGURE 5
Pesticides storage by farmers **(left)** and groundnut vendor operating at pesticide retail shop porch **(right)** in Karaye LGA.

TABLE 5 Farmers' understanding of pre-harvest interval (PHI).

Responses to pre-harvest interval awareness	Percentage
Do you know the meaning of pre-harvest interval?	
No	83
Yes	17
Waiting periods before harvest	
I don't know	97
7 days	3

to pesticides (Boateng et al., 2023), they contribute minimally to their supply in the study areas. The limited role of cooperatives could also reflect organizational weaknesses or a lack of focus on input distribution.

6.6 Pesticide use and disposal behavior

Table 7 shows that more than 90% of tomato farmers apply pesticides as a common practice to control pests. Among them, 57% suggested that they could distinguish counterfeit pesticides, while 33% took precautions by wearing protective equipment during pesticide spraying. Some commendable pesticide use practices were observed, demonstrating farmers' awareness of pesticide risks. For instance, most farmers (84%) wore facemasks while spraying pesticides.

Nevertheless, unsafe practices concerning the use of full PPE and the disposal of used pesticide containers were evident. A considerable number of farmers did not utilize goggles while applying pesticides, with only 16% protecting their eyes during pesticide application. The most alarming issue was farmers' response to pesticide disposal post-application. This finding corroborates other studies who reported that farmers used partial PPE with little face and personal protection during pesticide application in Ghana (Boateng et al., 2023), Cameroon (Oyekale, 2018), Nigeria (Madaki et al., 2024), and Pakistan (Mehmood et al., 2021).

Worryingly, 1% of farmers revealed that they dispose of pesticide containers in water bodies. This is a hazardous practice as it poses a significant risk to humans through the food chain

TABLE 6 Pesticides sources channel, usage guidance, and prevalence of counterfeit products.

	Frequency	Percent
Where did you buy pesticides?		
Agro-dealers	977	62.79
FMARD/Extension agents	12	0.77
Open markets	547	35.15
Cooperatives	2	0.13
Other	18	1.16
When you buy pesticides, do they explain how to store, use, and dispose of them?		
No	607	39.01
Yes	949	60.99
Are ineffective and counterfeit pesticides common in the market?		
No	508	29.81
Yes	1,196	70.19

TABLE 7 Farmer PPE use practices and pesticide disposal practices.

Panel 1: knowledge and PPE use	Frequency, (%)
Use pesticides	1,556 (91.31)
Distinguish counterfeit pesticide	885 (56.88)
Wear personal protective clothing	561 (36.05)
Protective boots	968 (62.21)
Mask	1,313 (84.38)
Goggles	253 (16.26)
Panel 2: disposal of used pesticide containers	**Frequency, (%)**
Reuse for another purpose	705 (45.31)
Burning	240 (15.42)
Throwing away on the farm	219 (14.07)
Bury them	116 (7.46)
Sell	118 (7.58)
Throwing away into a nearby bush	72 (4.63)
Throwing away into the village waste dump	58 (3.73)
Throwing into the drainage canals/streams/rivers	18 (1.16)
Gift it to the sprayer	5 (0.32)
Kept in my Store	5 (0.32)

Source: Survey result (2023).

and to non-target organisms (Okoffo et al., 2016). Because of the unavailability of designated pesticide disposal areas, most farmers are forced to burn (14%) or bury (12%) used containers. The high occurrence of this practice might be attributed to insufficient awareness and training about the proper utilization and disposal of pesticides, as evidenced by the participation of a mere 25.5% of farmers in pesticide disposal training. Only 4% of farmers mentioned that they disposed of waste containers in the community waste dump. A similar study in Nigeria revealed that 18% of farmers disposed of empty containers in the trash, while 65% disposed of leftover pesticide containers indiscriminately (Madaki et al., 2024). Owing to the lack of designated areas for disposing of used pesticide containers, numerous NGOs, government extension services, and pesticide suppliers advise burying waste pesticides and empty containers in areas away from farms and water bodies. However, these practices are also not environmentally friendly since buried chemical waste can contaminate soil and leach into the surface water, while burning pesticide containers generates environmentally persistent toxic emissions (WHO, 2019).

Farmers also reused pesticide containers for various purposes. Of the farmers who used pesticides, 42 and 13% reported reusing the pesticide container and disposing of it on the farm or in a neighboring residence, respectively. Empty containers are most commonly repurposed for performing ablutions before mosque prayers and storing seeds, which may pose significant risks of chemical contamination. This can lead to health issues, especially if pesticide residues remain in the containers. Exposure to such residues can cause acute poisoning or long-term health problems (WHO, 2019). Using containers for seed storage can also hinder germination rates and affect the overall health of the crops, leading to reduced yields and economic losses for farmers.

Only five farmers (<1%) gave empty pesticide containers to the SSPs. Since most SSPs know about pesticide hazards and work closely with reputable agro-dealers, this practice should be encouraged as a pathway to safe disposal practices. However, instead of providing it for free, as Boateng et al. (2023) argued, farmers could be encouraged to return pesticide containers to pesticide distributors and suppliers for a small fee or incentive. According to a study conducted in Iran, a portion of the money farmers paid for the pesticide was given back to them when they returned the pesticide containers to suppliers (Bagheri et al., 2021).

The WHO recommends that the best practice for pesticide container disposal is to destroy them in licensed high-temperature incinerators (WHO, 2019). However, this is unavailable to the farmers or expensive for them to adopt. Thus, it has become a common practice for smallholder farmers in low-income agrarian countries to mishandle pesticide containers, putting human health at high risk (Matthews, 2008; Bondori et al., 2018) and contributing to environmental degradation in developing countries (Mehmood et al., 2021).

6.7 Farmers' compliance with the pre-harvest interval period

The results showed that the average PHI for tomato growers (the period between the last application of a pesticide and the harvest) was 7.5 days (Table 7). A significant proportion of growers (40.5%) harvested tomatoes within 5 days, while 12% harvested within 3 days (Figure 6), indicating that many growers harvest tomatoes relatively soon after pesticide application. This raises concerns about potential pesticide residues on the harvested produce, which could pose health risks to consumers. If the applied pesticides have long-lasting effects, this could lead to consumer exposure to harmful chemicals. A similar study by Rahman and Chima (2018) also found that most farmers in developing countries harvest vegetables within 2–3 days after pesticide application, and the short PHI period is responsible for pesticide residues. In Nigeria, for instance, carcinogenic and non-carcinogenic health risks in children and adults have been estimated from exposure assessments to chlorinated pesticides, including exposure to hexachlorocyclohexane (HCH) residues on tomatoes and other vegetables (Odewale et al., 2021).

To understand how pesticide management awareness affects PHI adherence, we used a non-parametric test to disaggregate the results by pesticide disposal training. The results indicated that, on average, farmers who did not receive training waited 7.59 days before harvesting after pesticide application (Table 8). On the other hand, farmers who received training had a slightly shorter average waiting time of 7.43 days. The Mann–Whitney test (Prob > 0.83) showed that the PHIs for tomato growers with and without training did not differ significantly. This slight but insignificant difference suggests that while training may have some effect, it is not substantial. This indicates a need for improved training programs that convey the importance of adhering to recommended pre-harvest intervals.

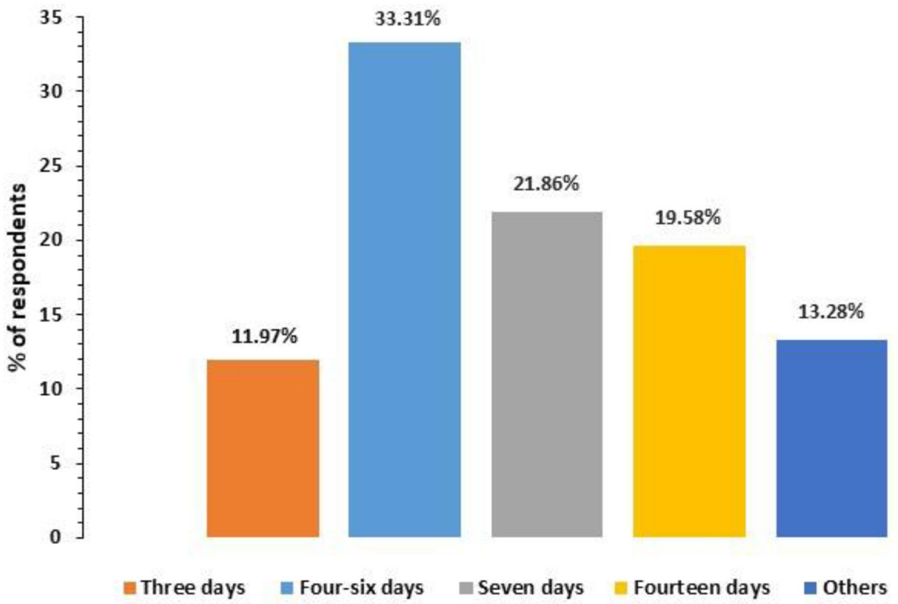

FIGURE 6
Percentage of farmers by pre-harvest interval period.

TABLE 8 Comparison of the pre-harvest interval by training attendance.

Variable	Pooled (N = 1,537)[a]			Non-attendant (N = 1,128)	Attending disposal training (N = 409)	Mann–Whitney test
	Mean	25th Percentile	**Median (p 50):**	Mean	Mean	Prob > |z|
Waiting periods before harvest (days)	7.55	5	7	7.59	7.43	0.833

[a] 19 farmers did not provide information on the number of days they waited, likely due to recall difficulties.

TABLE 9 Pairwise correlation between the three pesticide handling practices.

Pesticides management practices	Phi coefficient
Boots and protective clothing	0.43***
Goggles and protective clothing	0.19***
Mask and protective clothing	−0.57***
Disposal practices and protective clothing	0.09
Pre-harvest interval and protective clothing	0.21***

Level of significance (*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$).

6.8 Conditioning factors for pesticide handling and pre-harvest interval

Unlike previous studies that examined growers' decisions about pesticide handling and disposal practices using descriptive statistics (Damalas et al., 2008; Mengistie et al., 2017; Alex et al., 2018; Mubushar et al., 2019; Boateng et al., 2023), linear regression (Schreinemachers et al., 2017; Bagheri et al., 2021; Moda et al., 2022; Madaki et al., 2024), or bivariate models (Okoffo et al., 2016; Oyekale, 2018; Mehmood et al., 2021; Lelamo et al., 2023), the multivariate model we proposed in this study jointly estimated the factors affecting the adoption of safe pesticide use, disposal practices, and compliance with PHIs (Greene, 2012). The correlation matrix results (Table 9) indicated that the decisions to use PPE, acceptable disposal practices, and follow waiting intervals are interrelated, justifying the use of the multivariate probit model rather than univariate probit models. In the presence of contemporaneous correlation among the dependent variables, the use of a multivariate probit model provides efficient estimates compared with separate univariate models (Raguindin and De Vera, 2012; Ullah et al., 2016, as cited in Zulfiqar et al., 2021).

Figures 7 and 8 present the results of the multivariate probit model. Only significant variables are shown for ease of presentation, but the full estimation results are reported in the Supplementary material. Four key points stand out. First, socio-economic factors such as formal education, farm size, and age significantly influence safe pesticide use and disposal practices. We found that formal education is positively associated with PPE use, with educated farmers being 3.8 and 2.8 percentage points more likely to use protective clothing and rubber boots. This aligns with similar studies that found a positive correlation between education and pesticide-handling practices (Damalas and Khan,

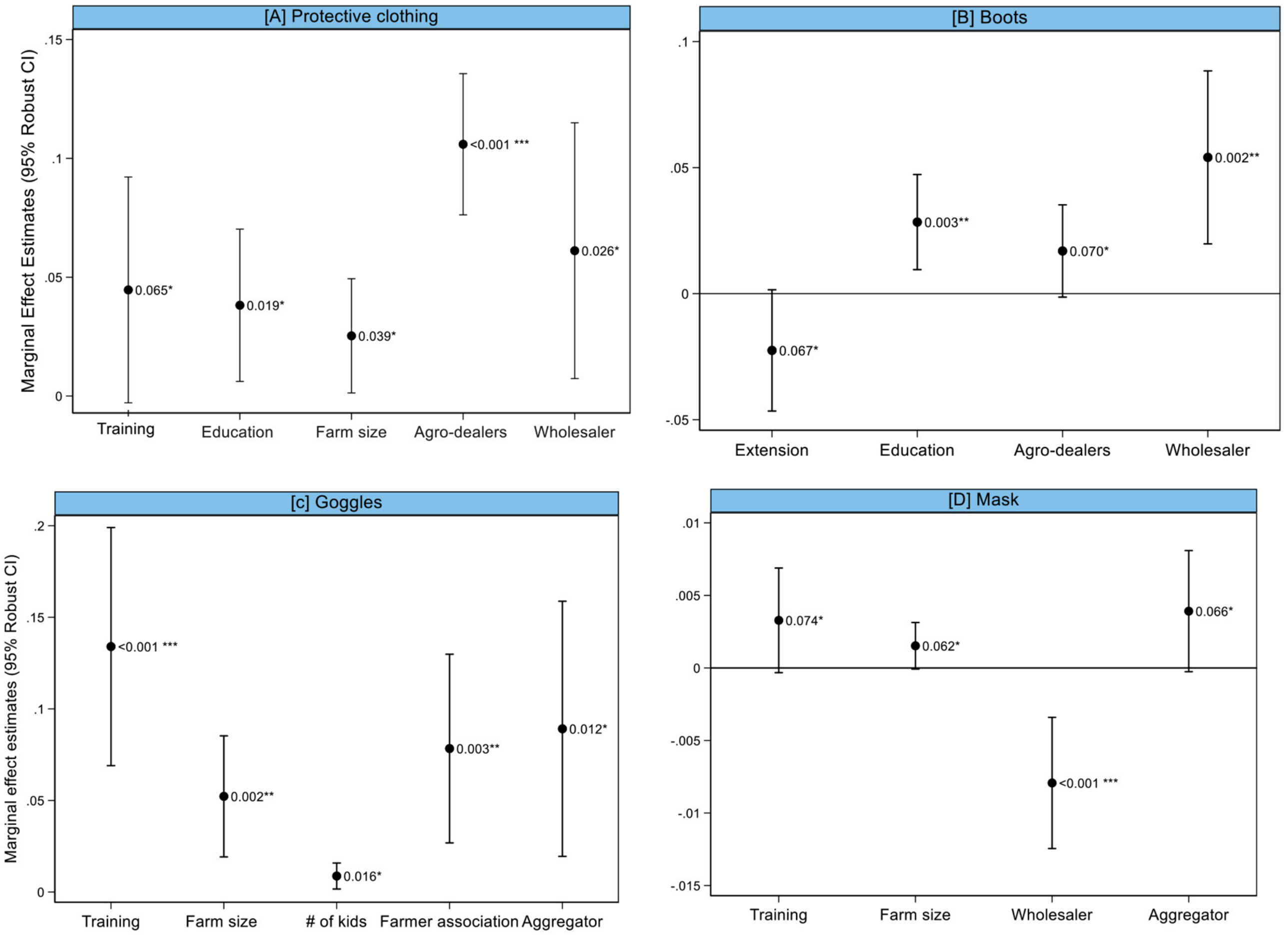

FIGURE 7
Estimated average marginal effects for the use of PPE. This figure displays marginal effects and their corresponding 95% confidence intervals as error bars. The marginal effects are estimated using the multivariate probit regression approach with $N = 1{,}542$ observations. The presence of an asterisk (*) indicates the level of significance (***$p < 0.01$, **$p < 0.05$, *$p < 0.1$)[a]. [a]Full models are reported in the supplementary information (see Table S1). The models are estimated with additional controls such as the age of the household head, training, access to extension, education, access to community spray service providers, farm size, number of children, membership of farmers' associations, purchase of pesticide from open markets and agro-dealers, and selling to midstream actors.

2017). Large farm sizes also encourage PPE use, potentially due to greater resource availability or higher risk exposure (Okoffo et al., 2016). Interestingly, age exhibited a positive relationship with acceptable disposal practices, with older farmers being 0.3 percentage points more likely to adopt safe disposal methods, which agrees with Madaki et al. (2024). Conversely, Damalas et al. (2019) reported that young farmers are more knowledgeable about pesticide handling than older farmers.

Second, pesticide knowledge and information access variables, such as training, emerged as critical factors in adopting safe pesticide practices. Farmers who received training were 19 percentage points more likely to dispose of leftover pesticides properly and exhibited greater use of protective equipment, such as clothing, goggles, and face masks, while spraying pesticides. This supports the premise that training is crucial for promoting safe disposal practices. However, we found a negative and significant effect of the source of pesticide purchase (both from open markets and agro-dealers) on acceptable pesticide container disposal practices. This agrees with the findings of Madaki et al. (2024) and Oludoye et al. (2021) in Nigeria. The prevalence of unprofessional and unskilled agro-dealers and retailers has limited the effectiveness of pesticide information and advice provision, leading to poor farmer awareness of safe pesticide disposal management. A key factor contributing to this issue is the lack of continuous surveillance and monitoring mechanisms by government institutions responsible for enforcing pesticide standards and guidelines in rural markets. Consequently, most farmers purchase pesticides without receiving professional support or adequate advice concerning pesticide usage and disposal practices. As noted by Madaki et al. (2024), farmers in Nigeria do not regard professional government agencies and farmers' associations as important sources of pesticide information. Similarly, Oludoye et al. (2021) reported that cocoa farmers in Nigeria complained about the government's limited involvement in providing pesticide-related information. Instead, farmers often rely on advice from retailers, whose primary focus is profit rather than health or environmental concerns.

Third, institutional factors such as extension services and membership of farmers' associations yielded mixed results. Extension service is negatively associated with the use of PPE

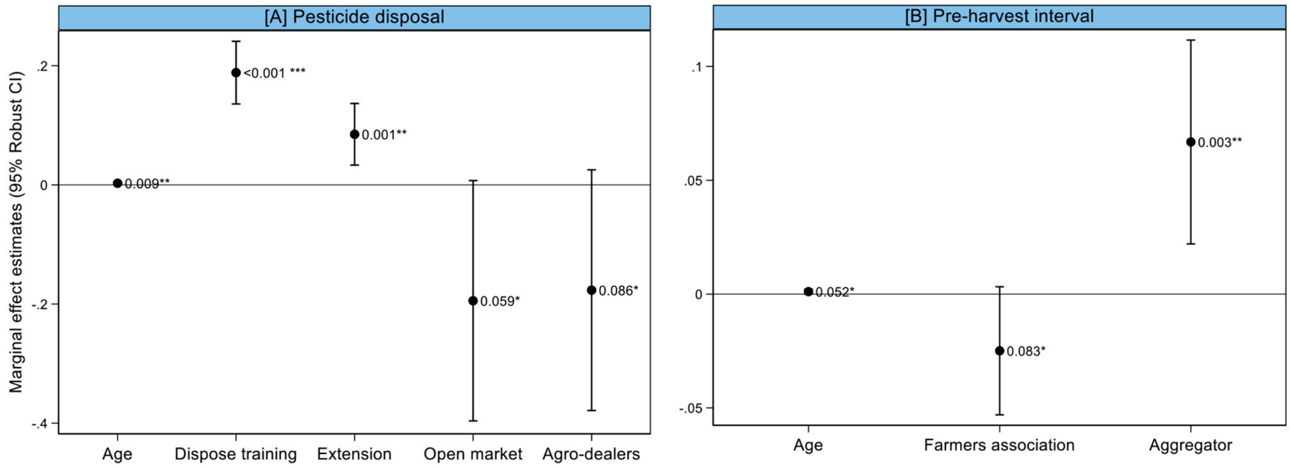

FIGURE 8
Estimated average marginal effects for pesticide disposal and waiting periods. This figure displays marginal effects and their corresponding 95% confidence intervals as error bars. **(A)** estimates acceptable pesticide disposal practices, while **(B)** shows the waiting periods after the last pesticide application. The marginal effects are estimated using the multivariate probit regression approach with $N = 1,542$ observations. The presence of an asterisk (*) indicates level of significance (***$p < 0.01$, **$p < 0.05$, *$p < 0.1$)[a]. [a] Full models are reported in the supplementary information (see Table S1). The models are estimated with additional controls such as the age of the household head, training, pesticide disposal training, access to extension, education, access to community spray service providers, farm size, number of children, membership of farmers' associations, the purchase of pesticides from open markets and agro-dealers, and selling to midstream actors.

such as rubber boots, which contrasts with other PPE use studies (see Madaki et al., 2024), while it agrees with the findings of Schreinemachers et al. (2017) in Southeast Asia. The extension services in Nigeria have historically been underfunded and under-resourced, leading to limited farmer engagement. As mentioned above, FMARD and extension agents contribute only a small fraction of pesticide supply to farmers (<1%). This low percentage may indicate farmers' preference for private channels through which to obtain PPE and advice more quickly, although it is ineffective (Oludoye et al., 2021). This is likely to be the reason for the positive effects of purchasing from agro-dealers on PPE use (wearing protective gear and boots) and the negative effects of extension access. However, extension access positively and significantly influenced acceptable disposal practices. Growers with access to extension services had an 8.5 percentage point greater likelihood of applying acceptable disposal practices, corroborating the findings of other studies (Damalas and Khan, 2017; Madaki et al., 2024). Hence, the effect of extension appears to be context specific.

This study found that membership of farmers' associations is negatively correlated with PHI adherence. Specifically, being a member of a farmers' association increases the likelihood of disregarding the required rest period by 2.6 percentage points. This finding can be explained by farmers' associations prioritizing aspects such as market access and profit maximization over food safety. Additionally, misinformation or over-reliance on peers within associations may perpetuate unsafe practices. Farmers may rely on incorrect or outdated advice from peers rather than seeking expert input. If some members misunderstand PHI requirements or fail to comply, their practices can influence others within the group, leading to lower adherence to PHI guidelines. This finding aligns with the observations of Guivant (2003), who noted that farmers often treat pesticide spraying as a preventive measure based on imitation of their neighbors. As a result, they violate the principles of the pesticide waiting period.

Despite the efforts of many stakeholders to train professional SSPs, it appears that community access to SSPs did not translate into safe pesticide use and handling. CropLife Nigeria and other stakeholders trained 3,094 SSPs in Nigeria in 28 states between 2016 and 2024. Although 13% of the trained SSPs are from Kano state, their service provision has not had a meaningful impact on farmers' pesticide-handling behavior. For farmers, the payoff of cheaper service providers (family/hired labor spray), as opposed to certified professionals, is typically unclear. On the one hand, in the absence of comprehensive and inclusive promotion and training, farmers frequently neglect the long-term effects of improper pesticide usage on the environment, occupational exposure, and food safety. Furthermore, the output market incentive is crucial for farmers to switch from conventional spraying to SSPs. Promoting such services might not be viable without training and market linkages to spur SSP adoption. Limited service offerings also hinder the commercialization of SSPs in Africa. A synthesis report on the implementation challenges of contract spraying services in Ghana, Ethiopia, Nigeria, and Kenya found that SSPs only engage in spraying services during seasonal agriculture production (Koomen and Moreno Echeverri, 2019). However, most horticultural production uses irrigation during the wet and off seasons. Thus, service diversification to account for seasonal attributes can increase the sustainability of SSPs' involvement in agriculture.

Fourth, marketing channels play a critical role in shaping farmers' pesticide use behavior. Interestingly, we found that growers who sell to midstream actors, such as wholesalers and aggregators, are more likely to practice safe pesticide use and comply with the PHI period. Compared to growers who marketed

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their produce exclusively through retailers or sell themselves, those who utilized midstream actors had a 6 and 5.4 percentage points higher probability of using protective clothing and rubber boots when spraying chemicals in tomato fields. Additionally, they exhibited a 6.7 percentage point greater likelihood of harvesting tomatoes at the recommended PHI time. This result may be attributed to the fact that wholesalers often supply major urban markets, such as the Mile-12 international vegetable market in Lagos, and supermarkets, where food safety standards are emphasized. These findings align with those of Marine et al. (2016), who reported that vegetable producers selling primarily to wholesalers exhibited a greater propensity to implement food safety procedures. Similarly, Fulponi (2006) highlighted how wholesalers leverage their purchasing power to pressure growers into adopting stringent food safety standards. Nevertheless, it is worth mentioning that both Marine et al. (2016) and Fulponi (2006) examined food safety practices within the context of formal contract arrangements, which are less common in many developing countries across the Global South. In such contexts, informal arrangements dominate, making the influence of market channels on safe pesticide use a unique area of exploration. Consumers' preferences for sustainably produced agricultural food further amplify the role of midstream actors in encouraging sustainable farming practices. For instance, Ruth and Jennifer (2023) argued that consumer attitudes, food preferences, and choices can influence agricultural supply chains. A recent study in Uganda, Ghana, Kenya, Pakistan, and Bangladesh (Tambo et al., 2024) corroborates this by demonstrating that food safety concerns significantly shape consumer choices in LMICs. The study also noted that consumers wary of pesticide use tend to avoid purchasing vegetables from street hawkers, opting instead for specialist shops that are perceived to adhere to higher food safety standards.

7 Conclusions and recommendations

This study investigated the determinants of pesticide use behavior among smallholder tomato farmers in Nigeria, revealing critical challenges in pesticide management. The study showed that farmers rely on chemical pesticides for pest control, including using highly toxic banned products. Despite some awareness of pesticide pictograms and the harmful effects of pesticides on human health, 83% of farmers lacked knowledge of PHIs, with 40% harvesting tomatoes within 5 days and 12% within 3 days of pesticide application. This lack of understanding underscores a significant gap in farmers' awareness of the effects of pesticide residue on consumers and themselves, as most farmers also consume their produce. While many farmers use PPE such as protective clothing and face masks, critical items like overalls, rubber boots, and eye protection are often neglected. The disconnect between knowledge and practice suggests a need for more effective training programs.

The present study also highlights the limited role of cooperatives and extension services in providing pesticide-related information. Farmers predominantly rely on agro-dealers and peer networks for pesticide advice, with 39% purchasing pesticides without receiving any guidance on proper usage, storage, and disposal. This explains the prevalence of unsafe practices in pesticide disposal, with many farmers reusing pesticide containers for hazardous purposes, such as performing ablutions and storing seeds. This behavior poses severe health risks and underscores the need for practical training and education on PPE use and safe disposal practices.

Empirical analysis revealed that training on pesticide disposal, formal education, and selling to midstream actors was positively correlated with safe pesticide practices, including PPE use and PHI adherence. However, membership of farmers' associations negatively influences PHI compliance. Furthermore, the unregulated pesticide supply chain contributes to improper disposal and handling practices, as unskilled agro-dealers fail to provide adequate guidance. To address these challenges, it is crucial to promote non-chemical pest management practices such as IPM. The reduction in pesticide use associated with IPM practices contributes to better environmental outcomes, and enhances food safety and the sustainability of agricultural systems. Training and education programs should focus on raising farmers' awareness of PHI, safe pesticide disposal, and the importance of PPE. Extension workers can provide pesticide-related information, educate farmers, and promote behavioral change. However, in the Global South, extension services are often underfunded and are unable to reach the entire farming community (Ruth and Jennifer, 2023), which is also the case in Nigeria. Small-scale farmers often rely on neighbors and peer networks for pesticide advice and related behaviors (Byamugisha et al., 2008; Rees et al., 2000; Ismet and Orhan, 2010). In this context, an effective way of providing pesticide capacity-building training and knowledge transfer to farmers is to promote participatory training approaches such as farmer field schools and field demonstrations at model farms (Dasgupta et al., 2007; Akter et al., 2018). Policymakers, pesticide companies, NGOs, and pesticide associations, including CropLife Nigeria, can support these initiatives by providing funding, personnel, and incentives to encourage farmer participation.

The government must also strengthen the regulation of pesticide supply chains. Enhanced supervision of agro-dealers, regular inspection of rural pesticide markets, and the introduction of returnable packaging systems can mitigate unsafe disposal practices and reduce environmental hazards. It is also important to update the technical knowledge of agricultural extension experts in terms of pest management and improve their capacity to reach more farmers with the aim of addressing information gaps (Abadi, 2018). Additionally, farmers' associations in Nigeria should broaden their services to include specialized training on safe pesticide use and PHI adherence besides general agricultural advice. Public–private partnerships can further promote safe pesticide practices by supporting training incentives and improving farmers' access to proper disposal infrastructure. These efforts should also be complemented by stronger regulatory frameworks and mechanisms to align farmer pesticide use practices with consumer preferences for safe products, as observed by the higher PHI adherence among farmers selling to midstream actors.

Finally, future research should explore the reasons underlying farmers' preference for chemical pesticides over IPM, including cost-effectiveness and contextual factors. Furthermore, our research has focused on the pesticide use behavior of farmers as one group of agricultural supply chain actors, but we disregarded agro-dealers, retailers, and consumers (see Ruth and Jennifer, 2023), all of whom play crucial roles in this system. Investigating the roles of these actors in shaping pesticide use behaviors is equally important. Additionally, understanding the mechanisms by which midstream actors influence safe pesticide practices and food safety in an informal market context can provide valuable insights for policy interventions in developing countries.

Data availability statement

The datasets analyzed during the current study are available in the IITA CKAN data repository [Plastic crates RCT experiment in Nigeria - Datasets - IITA].

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

MY: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LL-T: Conceptualization, Methodology, Supervision, Writing – review & editing. RM: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. TW: Conceptualization, Investigation, Writing – review & editing. TF: Writing – review & editing. OO: Investigation, Methodology, Writing – original draft, Writing – review & editing. FY: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. JC: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. SF: Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. TA: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

RM was employed by company CropLife Nigeria.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1520943/full#supplementary-material

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