frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 28 February 2025
DOI 10.3389/fsufs.2025.1509230



OPEN ACCESS

EDITED BY
Mohamed Ait-El-Mokhtar,
Hassan II University of Casablanca, Morocco

REVIEWED BY
Saeed ur Rahman,
Shanghai Jiao Tong University, China
Ashutosh Mall,
Indian Sugarcane Research Institute (ICAR), India

*CORRESPONDENCE
Adetomiwa Kolapo
✉ kolapoadetomiwa@gmail.com

RECEIVED 11 October 2024
ACCEPTED 27 January 2025
PUBLISHED 28 February 2025

CITATION
Kolapo A, Ojo TO, Khumalo NZ, Elhindi KM, Kassem HS and Filusi OJ (2025) Enhancing land nutrient through rhizobia biofertilization: modeling the joint effects of rhizobium inoculants and improved soybean varieties on soybean productivity in North Central, Nigeria.
*Front. Sustain. Food Syst.* 9:1509230.
doi: 10.3389/fsufs.2025.1509230



# Enhancing land nutrient through rhizobia biofertilization: modeling the joint effects of rhizobium inoculants and improved soybean varieties on soybean productivity in North Central, Nigeria

Adetomiwa Kolapo[1]*, Temitope O. Ojo[1,2,3], Nolwazi Z. Khumalo[4], Khalid M. Elhindi[5], Hazem S. Kassem[6] and Olajide Julius Filusi[7]

[1]Department of Agricultural Economics, Obafemi Awolowo University, Ile-Ife, Nigeria, [2]Department of Plant, Food and Environmental Sciences, Faculty of Agriculture, Dalhousie University, Truro, NS, Canada, [3]Disaster Management Training and Education Centre for Africa, University of the Free State, Bloemfontein, South Africa, [4]Department of Agriculture, University of Zululand, Richards Bay, South Africa, [5]Department of Plant Production, College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia, [6]Department of Agricultural Extension and Rural Society, Faculty of Agriculture, Mansoura University, Mansoura, Egypt, [7]Department of Agricultural Extension and Rural Development, Obafemi Awolowo University, Ile-Ife, Nigeria

Improving bacterial nitrogen fixation in grain legumes is central to the sustainable intensification of agriculture using rhizobia biofertilization. However, few studies have evaluated their joint impact on productivity using improved soybean varieties. Using household-level data from North Central Nigeria, this study explored the joint effects of the adoption of improved soybean varieties and the use of rhizobium inoculants on soybean yield and farm income. As both observed and unobserved factors may affect farmers' decisions to adopt improved soybean varieties, a recursive bivariate probit (RBP) model is used to address the selection bias issue associated with the adoption of improved soybean varieties. Furthermore, a selectivity-corrected ordinary least square (OLS) model is applied to estimate the joint effects of the adoption of improved soybean varieties and usage of rhizobium inoculants on soybean yield and farm income. The results of the RBP model reveal a negative selection bias due to unobserved factors. After controlling for this selection bias, the results show that the adoption of improved soybean varieties increases the probability of using rhizobium inoculant by 25.2% as a complementary technological package. Soybean yield and farm income are positively and statistically significantly impacted by the adoption of improved soybean varieties (ISV). In the same vein, the adoption of rhizobium inoculants shows a positive and statistically significant effect on the yield and income from soybean production. This implies that farmers' use of rhizobium inoculants helps them increase their farm yield while also improving their income. To provide more robust insights into this study, a robustness check, using unconditional quantile regression at different quantiles, was estimated. The findings demonstrate the heterogeneous effects of rhizobium inoculants and the adoption of improved soybean varieties adoption on soybean yield and farm income. Our finding generally confirms the significant role of the adoption of improved soybean varieties in facilitating farmers' use of rhizobium inoculants as a complementary package.

KEYWORDS

**rhizobium inoculant, improved soybean varieties, recursive bivariate probit, Kwara, Benue, Nigeria**

## 1 Introduction

Soybeans (*Glycine max*) are grown in tropical, sub-tropical, and temperate regions. The crop known as "poor man's meat," or soybean, is an essential pulse that grows well in a variety of climates (Tafida et al., 2022). Nigeria had its first successful soybean production in 1937, in the region of Benue State. Nigeria has seen an increase in soybean farming due to the nutritional value, economic significance, and variety of domestic uses of the crop (Mahama et al., 2020). According to Haddabi (2020) and Ugbabe et al. (2017), soybeans are widely regarded as an adaptable crop with approximately 365 suitable uses in human and animal meals as well as other industrial purposes. Due to its wide range of domestic uses, nutritional value, and economic significance, its cultivation has increased in Nigeria. Therefore, it is anticipated that there will be a significant market for soybean products in Nigeria, particularly among commercial users in the food, paint, pharmaceutical, and confectionary industries (Mahama et al., 2020). By increasing soil fertility through nitrogen fixation, allowing for a longer period of ground cover throughout the cropping sequence, and managing the parasitic weed *Striga hermonthica*, soybeans can further improve the sustainability of intensified cropping systems (Dugje et al., 2009). Domestic soybean output of Nigeria is on the rise, but due to low-yield, subpar agronomic, and post-harvest procedures, it still trails behind the rapidly expanding demand from the poultry industry for soybean meal and vegetable oil processors (USAID, 2016). Annual soybean production of Nigeria has reached over 850,000 metric tons, but this is still insufficient to bridge the domestic demand and supply gap for the crop and lessen the significance of soybeans in the nation (Amesimeku and Anang, 2021). Although Nigeria is listed as the second-largest producer of soybeans in Africa, there is a shortage in output due to the 1.275 million tons of domestic demand for soybeans of the country (Amesimeku and Anang, 2021). However, due to a consistent rise in the consumption of poultry products, the demand for soybeans is anticipated to reach 2.3 million MT by 2027 (USAID, 2016).

FAOSTAT (2021) estimations show that Nigeria is the continent's second-largest producer of soybeans after South Africa; nonetheless, their average output of less than one ton per hectare falls short of the potential production of the crop of more than three tons per hectare (Ronner et al., 2016). From the mid-1970s to the present, research institutes have undertaken initiatives to enhance the current soybean varieties in order to boost production in Nigeria (Vanlauwe et al., 2019). The International Institute for Tropical Agriculture (IITA) was a notable research institute that began studying soybeans in the 1970s and has since made significant efforts to increase the crop yield (Abdullahi, 2004). Idrisa et al. (2010) posited that commercial soybean production has increased and dispersed throughout Nigeria as a result of the introduction of improved soybean varieties. Nigeria has a great deal of potential for producing soybeans, but the average yield of the country is low due to several production barriers, including salinity, low use of P fertilizer, poor crop management practices, and poor nodulation of soybean cultivars with the native *Rhizobium* sp. (Ewansiha et al., 2022). Regrettably, the majority of lands have degraded as a result of many man-made and natural forces, lowering their quality. Reducing land degradation and improving its chemical fertility condition are two benefits of developing resilient agricultural systems, such as using internal soil resources (Omeke, 2016).

While applying chemical fertilizers is an everyday practice in agricultural production to improve crop yield and soil fertility, its excessive application can cause a host of environmental issues, such as decreased soil productivity and biodiversity (Yang et al., 2018; Khalid et al., 2022a, 2022b, 2023), pollution of the environment (Drijber et al., 2000; Kedi et al., 2024; Rehman et al., 2024; Muhammad et al., 2024), and acidification of the soil (Ahmad et al., 2013; Xiao et al., 2021; Xie et al., 2021). To lessen the negative effects of fertilization, various strategies are currently being used in agriculture, including fallowing, organic substitution (Dai et al., 2019; Ji et al., 2020; Zhang et al., 2021), planting green manure (Zhang et al., 2017; Ma et al., 2021), biofertilizer promotion (Wu et al., 2005; Castro et al., 2020), and planting green manure (Zhang et al., 2017; Ma et al., 2021). Because biofertilizers are effective and environmentally friendly, they have become a hot topic for research. According to Abd-Alla et al. (2014) and Koskey et al. (2017), they can decrease fertilization rates with the appropriate nutrient elements, activate fixed nutrients in the soil, and promote growth and absorption by the root system. These soil modifications can minimize crop damage, eradicate dangerous bacteria, and boost good bacteria (Igiehon and Babalola, 2017; Schütz et al., 2018). Rhizobia from soybeans are biofertilizers that aid in nitrogen-fixing and reduce emissions (Soumare et al., 2020).

Rhizobium, a common Gram-negative soil bacterium, can encourage the production of root nodules and symbiotic nitrogen fixation in legumes (Han et al., 2020). Positive impacts of rhizobium on crop growth and nutrient absorption include increased phosphorus and iron absorption as well as increased generation of plant hormones that stimulate crop growth. They can also increase crop productivity, reduce the occurrence of pests and diseases, and increase the number of helpful microbes (Zhuang et al., 2007; Ahemad and Kibret, 2014). Gibberellin, a plant hormone generated by rhizobia, causes host legume nodules to grow (Nett et al., 2022). Moreover, rhizobia inoculation has been shown to increase crop yields, including soybeans (Ronner et al., 2016). Additionally, it has been shown that the usage of enhanced crop varieties in conjunction with rhizobia has a stronger effect than rhizobia inoculum alone. Co-inoculation of *Azospirillum brasilense* and *Bradyrhizobium japonicum* may increase the nodulation rate and yield of soybeans (Hungria et al., 2013; Barbosa et al., 2021; Moretti et al., 2021). Due to the potential impact of rhizobia inoculum and the use of improved soybean varieties to increase smallholder farmers' yield, several agriculture-for-development projects implemented in North Central Nigeria, especially in Kwara State, have promoted the use of improved varieties and good crop management practices such as inoculant technology to soybean farmers to increase crop production and improve the welfare of their households. Oyenpemi et al. (2023) stated that off-taker demand-driven agriculture (ODDA) is a Kwara State intervention program that was started in 2017. It is designed to increase food production, reduce poverty, raise living standards, and stimulate employment in the agricultural sector while broadening the State's economic base. In addition to matching farmers with off-takers, the program offers seedlings, fertilizers, pesticides, and other crop supplies. The target audience of the program consists of farmers who grow rice, maize, soybeans, and cassava. This project worked to improve the productivity and the adoption of soybean varieties and associated technologies such as rhizobia inoculum because of the role of this crop in improving soil fertility and human nutrition. The technologies disseminated included improved varieties and associated technologies and also phosphorus fertilization to increase yield. Despite these interventions, no detailed study has been undertaken to empirically evaluate the joint impact of the adoption of these technologies (rhizobium inoculants and improved soybean varieties) on the yield of soybeans in the region. Several studies have documented the adoption of improved agricultural technologies in Nigeria (Korir et al., 2017; Thilakarathna and Raizada, 2017; Zilli et al., 2021; Kolapo et al., 2020, 2022, 2023; Ojo et al., 2021). However, the focus of the previous studies is largely on rice, maize, cassava, and cowpeas. In addition, several studies (Dai et al., 2019; Ji et al., 2020; Zhang et al., 2021; Ahemad and Kibret, 2014; Trabelsi and Mhamdi, 2013; Nett et al., 2022; Liu et al., 2022; Pereira et al., 2019; Marks et al., 2015; Yanni et al., 2016; Mehboob et al., 2009) previously carried out on the use of rhizobia inoculants in crop production are mostly associated with field experimental research. In Nigeria, usage of rhizobium inoculants for soybean production among smallholder farmers is getting popular. Despite this, there is a gap in knowledge about the potential effects of the use of rhizobia inoculant among soybean farmers. While a few studies have documented the adoption of soybeans in Nigeria, no attention has been given to modeling the adoption of soybean production technologies since its introduction to farmers. The objectives of this study were to assess the joint impact of the adoption of improved soybean varieties and rhizobium inoculants on soybean yield among smallholder farmers in North Central, Nigeria. The combination of recursive bivariate probit (RBP) and seemingly unrelated bivariate probit (SUBP) models in analyzing agricultural technology adoption introduces a novel methodological framework with several groundbreaking aspects: The RBP model explicitly captures causal relationships, such as when the adoption of one technology influences the likelihood of adopting another. This is crucial for disentangling the sequential or dependent nature of farmers' decisions under constraints such as resource availability or knowledge diffusion. The SUBP model, in contrast, is designed to model contemporaneous interdependence, addressing situations where farmers make simultaneous adoption decisions influenced by correlated unobserved factors (e.g., risk attitudes or market access). Combining these models enables researchers to account for both recursive (causal) and simultaneous (correlated) relationships, providing a holistic understanding of decision-making dynamics.

Our results would provide novel insights into the joint effects of the wider use of improved soybean varieties and rhizobium inoculation on soybean yield and a theoretical basis for microbial fertilizer utilization among smallholder farmers while also providing information for government, donor organizations, and research institutions, and other development partners to promote policies and strategies to enhance the adoption of biofertilization such as rhizobium inoculants.

The remainder of the paper is organized as follows. Section 2 reviews the conceptual framework. Section 3 explains the methodology used. Section 4 describes the econometric framework used in our empirical analysis. Section 5 presents the empirical results and discusses the possible mechanisms through which improved soybean varieties and rhizobium inoculants may affect soybean yield. Section 6 concludes.

## 2 Conceptual framework

Technology adoption is often modeled by way of a choice between two alternatives, the old and the new (Kolapo et al., 2021a, 2021b). The ith farmers' utility derived from using improved soybean varieties coupled with rhizobium inoculants or local varieties of soybeans is given by $U_{ij}$ with $j=(0,1)$ for the local and improved varieties, respectively. This is defined as Equation 1:

$$U_{ij} = \mu_{ij} + \varepsilon_{ij} \quad j = 0,1 \text{ and } i = \{1,,2,,\ldots n) \tag{1}$$

where $\mu_{ij}$ is an efficient utility—a non-stochastic function of explanatory and unknown factors, and $\varepsilon_{ij}$ is an unobservable random utility part that accounts for variation in taste together with stochastic errors.

Using the random utility theory described by Tafida et al. (2022), farmers' adoption of rhizobium inoculants and improved soybean varieties would occur when the expected utility associated with the adoption, $U_{1i}$ is greater than that associated with non-adoption, $U_{0i}$. It is assumed that based on the principle of rationality the $i^{th}$ farmer will make an adoption decision that leads to the highest utility. Thus, the $i^{th}$ farmer, who wishes to maximize his utility, will adopt rhizobium inoculants and improved soybean varieties if the random utility $U_{1i}$ .> $U_{0i}$. $A_i$ is a qualitative variable that indexes farmers' adoption decisions. If $U_{1i} < U_{0i}$ then $A=0$ and $U_{1i}$ .> $U_{0i}$ then $A=1$.

The utility of the farmers cannot be observed, but what is observable is the choice he makes between the two varieties, which is an indication of the one that offers the highest utility. Hence, a binary random variable is used to model the choice of the farmer of either variety. The probability of rhizobium inoculants and the adoption of improved soybean varieties can thus be presented as follows, where Λ is the cumulative distribution function of $\Sigma i_0 \ \Sigma i_1 = \zeta_i$ and R is a vector of parametric coefficients to be estimated; Xs are vectors of independent/explanatory variables. The likelihood of a farmer adopting rhizobium inoculants and improved soybean varieties is a function of the farmers' socioeconomic characteristics, institutional variables, and the stochastic error term. If $U_{1i}$ is normally distributed, then is the cumulative density function consistent with the logistic model (Ogunyemi et al., 2021). An adopter is a farmer who cultivated any of the improved soybean varieties, including the early and extra-early maturing varieties—TGX1904-6F, TGX1835-10F, TGX 1951-3F, and TGX 1955-4F on any of their fields in the 2022 cropping season and also uses rhizobium inoculants as biofertilizers. A non-adopter of ISV is any farmer who cultivated older varieties that are late maturing, low yielding, and susceptible to rust disease (e.g., TGX1448-12E) in the 2022 cropping season. In this paper, we study the causal effect of the adoption of improved soybean varieties on the usage of rhizobium inoculants. We employ the recursive bivariate probit (RBVP) model with an instrumental variable in order to solve the endogeneity issue. In the absence of a suitable instrument variable (IV), the RBVP model yields an asymptotically unbiased estimator. To the best of our knowledge, it has not been utilized to investigate the combined effects of complementary technology packages, although it has assisted researchers in obtaining achieving results in many fields of economic research. Our analysis employed the seeming1y unre1ated bivariate probit (SUBP) model in addition to the RBVP model with an IV to model the combined effect of the adoption of improved soybean varieties and rhizobium inoculant on soybean production.

# 3 Methodology

## 3.1 Study area

The research was conducted in the north-central region of Nigeria. According to Balogun (2009), the region is situated between latitudes 8ºN and 10ºN and longitudes 3°E and 10°E. The tropical continental climate of north-central Nigeria is typified by a broad range of annual temperature variations and limited rainfall, which are dependent on the region and time of year. According to Maikasuwa and Ala (2013), the average yearly temperature is between 24 and 37 degrees Celsius, and the average annual rainfall is between 100 and 200 $cm^3$. The rainy season, which runs from April to October, and the dry season, which begins in December and lasts until March, define the climate of north-central Nigeria. The moist tropical maritime air mass of the southwest trade winds signals the recession of harmattan for the rains. Warm, bright days are typically indicative of this point, with the maximum temperatures occurring in March and April. According to Maikasuwa and Ala (2013), the soil resources of the area are either friable, porous, coarse-grained sandy, or lateritic, typically with a gray or reddish color and low fertility. With fertile ground for the rearing of sheep, goats, and cattle, agriculture is the people's primary source of income. Approximately 80% of the population works directly in peasant agriculture, specializing in rice, sweet potatoes, cassava, sorghum, citrus, spices, pepper, groundnut, soybean, and bambara nuts. Numerous crop species are supported by the soil. These crops provide a marketable surplus for cash in addition to meeting a large portion of the subsistence food needs of the typical farm family. The decision to focus on Benue and Kwara States, while excluding other states in the same agroecological zone, was because Benue and Kwara States offer a representative mix of the agroecological and socioeconomic characteristics, typical of the Guinea Savannah and Sudan Savannah zones. They encompass high agricultural productivity potential (e.g., fertile soils in Benue, often called the "food basket of Nigeria"), and diverse cropping systems, including legumes such as soybeans that are central to the study.

Including these two states ensures a broad but manageable scope that aligns with the objectives of the study. While other states share similar agroecological characteristics, their inclusion might introduce overlapping insights without significantly enhancing the depth or diversity of the analysis.

The study employed a multistage sampling procedure to choose those who participated. In the initial phase, two states—Benue and Kwara—that are part of the same agroecological region were purposefully chosen. Using a purposive sample, two local government areas (LGAs) were chosen from each state in the second step, taking into account the large number of smallholder soybean farmers in these areas. Five villages were chosen at random from each of the four LGAs for the third stage. Following Tesfahunegn et al. (2016), the sample size for the study was established using the sample determination formula as outlined by Cochran (1977) at a 95% confidence level and a 5% margin of error. This allowed for the selection of 12 farmers from each of the five villages that had previously been chosen to provide 480 respondents who were interviewed for the study. The study area map is depicted in Figure 1.

Structured questionnaires were used to collect data from the respondents. Data on socioeconomic characteristics such as age, gender, educational status, farming experience, farm size, household size access to financial supports, membership of farmers' associations, access to weather information, access to irrigation facilities, access to extension services, and years stayed in the community were collected. Furthermore, data on varieties of soybean being cultivated, costs of inputs and outputs, yield and income from soybean production, access to machinery, receiving training and skill acquisition, and types of land enhancement technologies implemented on their farm were all collected. Data enumerators were incorporated during data collection after receiving training before the start of data collection. Data were collected with the use of the Open Data Kit (ODK) application. The choice of ODK application for data collection was due to its capacity to eliminate the need for manual data entry, reducing transcription errors and speeding up the data collection process. Built-in features such as skip logic, conditional questions, and real-time data validation minimize errors during data collection, and its ability to allow for customization of surveys to fit specific research needs supports large-scale data collection with multiple enumerators. During its implementation for the data collection exercise, we were faced with challenges such as battery drain, screen damage, or software compatibility issues, particularly in rugged field conditions among others. Data cleaning was carried out which was later transferred into STATA 15 for data analysis.

Gatekeeper permission was also obtained from the community leaders of the selected communities in the Local Government Areas in Benue and Kwara States. The ethical principles of respect for person, anonymity and confidentiality, beneficence, and principle of justice were all observed in the course of the study. For instance, data collection was only done after informed consent had been obtained from the respondents. Respondents were asked for their consent verbally before the commencement of the interview. Informed consent was obtained verbally from the respondents, and only those respondents who gave their consent verbally were interviewed. All respondents, irrespective of their ethnicity and creed, were treated fairly and equally throughout the conduct of the study.

## 3.2 Econometric framework

### 3.2.1 Recursive bivariate probit

Households decide (self-selection) whether to adopt the improved soybean varieties and rhizobia inoculants, depending on their welfare and other socioeconomic and technological factors, which leads to the potential endogeneity issue of the adoption variables of improved soybean varieties and rhizobia inoculants in an econometric estimation. Rhizobia inoculant is a complementary technology package to improved soybean varieties, and as such, its adoption depends on the adoption of improved soybean varieties. When analyzing the impact of a binary endogenous treatment variable (i.e., adoption of improved soybean varieties) on a binary outcome variable (i.e., rhizobia inoculants), previous studies have suggested different approaches, such as the PSM method (Minah, 2022; Shimada and Sonobe, 2021), endogenous switching probit (ESP) model (Lokshin and Sajaia, 2011; Nkegbe et al., 2022), and recursive bivariate probit (RPB) model (Addai et al., 2022; Li et al., 2021). Among them, the PSM method fails to correct for endogeneity issues originating from unobserved factors (e.g., an individual's innate ability and motivation), while the ESP model cannot estimate a direct effect of the adoption of improved soybean

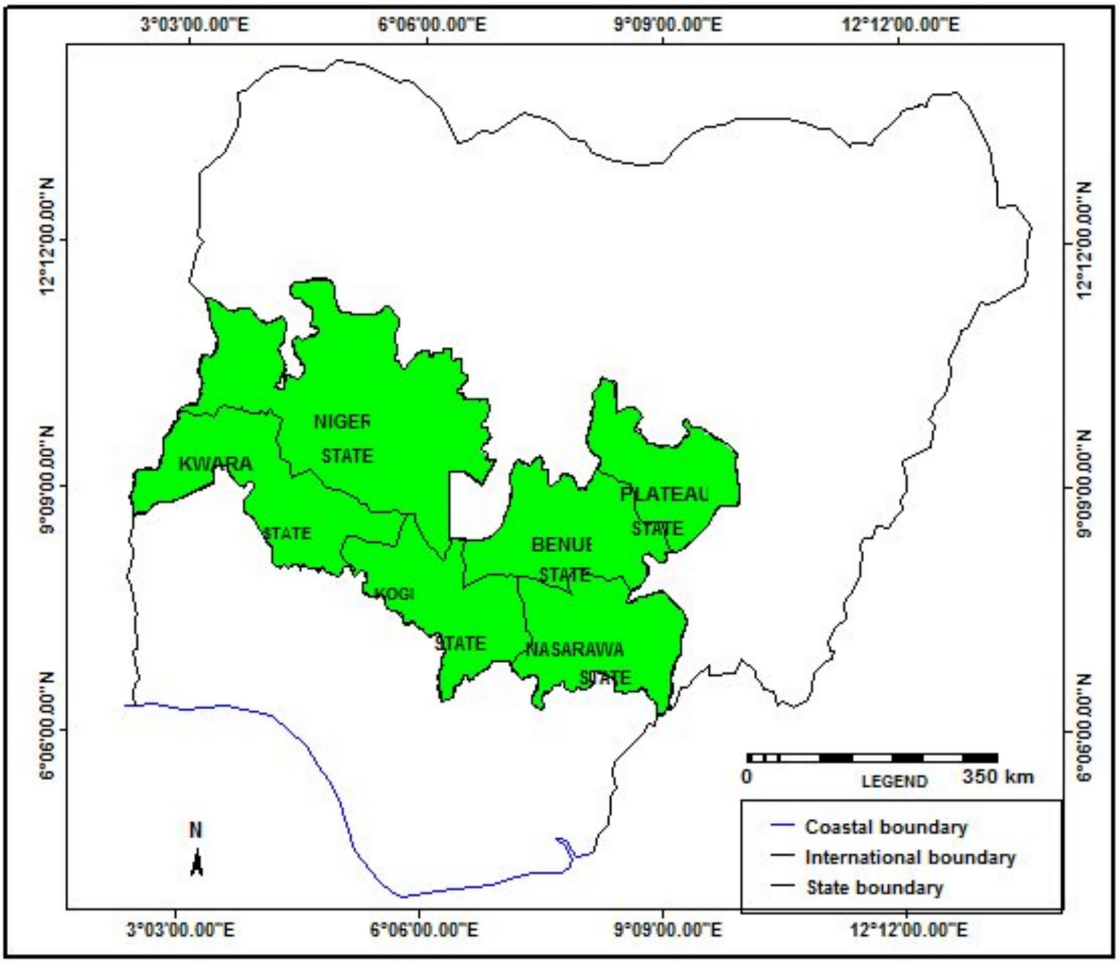


FIGURE 1
Map of Nigeria showing the North central region. Source: Google map.

varieties on the adoption of rhizobia inoculants. In comparison, the RBP model addresses the endogeneity issue from both observed and unobserved factors, and it can estimate a direct marginal effect of the adoption of improved soybean varieties on rhizobia inoculants. Therefore, this estimation uses the RBP model. The RBP model estimates two equations (Addai et al., 2022; li et al., 2021). One describes the probability of the adoption of improved soybean varieties based on Equation 2, and another explains the impact of the adoption of improved soybean varieties on households' use of complementary package (rhizobia inoculant) based on Equation 3:

$$Ii* = \eta iXi + \xi iIVi + \tau i, Ii = \begin{cases} 1, if \ Ii* > 0 \\ 0, otherwise \end{cases} \tag{2}$$

$$R_i^* = \alpha_i I_i + \beta_i X_i + \varepsilon_i, \ R_i = \begin{cases} 1, if \ Ri* > 0 \\ 0, otherwise \end{cases} \tag{3}$$

where $I_i$* i is a latent variable representing the probability that a household i adopts improved soybean varieties, which is determined by the observed binary variable $I_i$ ($I_i = 1$ for improved soybean varieties adopters and $I_i = 0$ for non-adopters); $R_i$*refers to a latent variable that represents the propensity of the adoption of rhizobia inoculant, which is determined by the observed binary variable $R_i$ ($R_i = 1$ for rhizobia inoculant users and $C_i = 0$ for non-users); $X_i$ is a vector of exogenous variables; $IV_i$ refers to an instrumental variable (IV), which is used for RBP model identification; $\eta_i$, $\xi_i$, $\alpha_i$, and $\beta_i$ are parameters to be estimated; $\tau$i and $\varepsilon_i$ are error terms.

The selection of instrumental variables (IVs) for the recursive bivariate probit (RBP) model is critical because it addresses the issue of endogeneity in the recursive structure. Endogeneity arises when the explanatory variable in the first equation (e.g., the adoption of Technology A) is influenced by unobserved factors that also affect the dependent variable in the second equation (e.g., the adoption of Technology B). IVs help isolate the exogenous variation in the endogenous explanatory variable to ensure unbiased and consistent estimation. The variables used as instruments included awareness of improved soybean varieties and rhizobia inoculants, years stayed in the community, and ownership of land. The rationale for the choice of instruments is usually based on the likelihood that the variables are capable of influencing farmers' decision to adopt new technology but may not directly influence the response variable (e.g., income, revenue, and yield). In this study, the selected variables as instruments were based on the premise that they are capable of influencing farmers' adoption decisions but may not directly influence the yield from soybean production. Statistically, we conduct a Pearson correlation analysis to test the validity and effectiveness of the IV. The full-information maximum-likelihood estimator simultaneously estimates Equations 2, 3. This procedure generates a correlation coefficient between the two error terms in Equations 2, 3, that is, $\rho_{\tau\varepsilon} = \text{corr}(\tau_i, \varepsilon_i)$. If $\rho_{\tau\varepsilon}$ is statistically significant, it would suggest the presence of selection bias arising from the unobserved factors (Addai et al., 2022), and estimate the impact of the adoption of improved soybean varieties on the use of rhizobia inoculants using other approaches such as PSM or simple probit model may generate biased estimates. When assessing the validity of instrumental variables (IVs), specific thresholds are used to evaluate the strength and significance of the correlation between the IVs and the endogenous variable. These thresholds are critical in ensuring the IVs are sufficiently strong to provide unbiased and consistent estimates in econometric models such as the recursive bivariate probit (RBP). A rule of thumb is that the F-statistic should be greater than 10 to avoid weak instrument problems. If $F \leq 10$, the IVs are considered weak, leading to potential bias in the second-stage estimates. In addition, a higher partial $R^2$, which measures the proportion of variance in the endogenous variable explained by the IVs, indicates stronger instruments. While there is no strict threshold, higher values are preferred.

### 3.2.2 Modeling the joint effects of the adoption of improved soybean varieties and rhizobia inoculants on soybean yield [seemingly unrelated bivariate probit (SUBP) model]

To examine the joint effects, we assume that soybean yield is a function of the adoption of improved soybean varieties and rhizobia inoculants, and a vector of explanatory variables. The regression equation for soybean yield can be rewritten as follows:

$$Y_i = \gamma_i I_i + \delta_i R_i + \varphi_i X_i + \varpi_i \tag{4}$$

where $Y_i$ refers to yield/income, which is measured in kilograms or naira/ha; $I_i$, $R_i$, and $X_i$ are variables defined earlier; $\gamma_i$, $\delta_i$, and $\varphi_i$ are parameters to be estimated; $\varpi_i$ is an error term. $\gamma_i$ and $\delta_i$ are parameters capturing the impacts of improved soybean varieties and rhizobia inoculants on soybean yield, respectively. Equation 4 can be estimated using an ordinary least square (OlS) regression model.

As discussed earlier, the adoption variable of improved soybean varieties ($I_i$) is endogenous in Equation 4, because farmers select themselves as improved soybean varieties adopters or non-adopters. The use of rhizobia inoculant ($R_i$) is also potentially endogenous in Equation 4 due to the similar self-selection issue of becoming rhizobia inoculant users or non-users. The endogeneity issue of the adoption of variables of improved technologies has been discussed in previous studies (Kolapo et al., 2023; Ojo et al., 2021). Failing to address the endogeneity issues associated with improved soybean varieties and rhizobia inoculant variables would produce biased estimates regarding their joint effects on soybean yield. Following previous studies (Ma et al., 2018; Wooldridge, 2015), we employ a two-stage selectivity-corrected OLS model to estimate the unbiased impacts of improved soybean varieties and rhizobia inoculant on soybean yield. In the first stage, the two equations of improved soybean varieties and rhizobia inoculants are jointly estimated using a seemingly unrelated bivariate probit (SUBP) model. The SUBP model simultaneously estimates an adoption of improved soybean varieties equation and rhizobia inoculant equation. Unlike the RBP model estimation, the adoption variable of improved soybean varieties is removed from Equation 3. in the SUBP model estimation to avoid a reverse causality relationship between the adoption of improved soybean varieties and rhizobia inoculant usage. The results estimated by the SUBP model are used to generate predicted variables for the endogenous factors. In the second stage, the adoption variable of predicted improved soybean varieties and variable of predicted rhizobia inoculant, which controls for the endogeneity issues, are used to replace the original variables in Equation 4. Therefore, the following selectivity-corrected OlS model can be estimated:

$$Y_i = \zeta_i I'_i + \lambda_i R'_i + \psi_i X_i + \omega_i$$

where $Y_i$ and $X_i$ are variables defined previously; $I'_i$ and $R'_i$ are adoption variables of predicted improved soybean varieties and the variable of predicted rhizobia inoculant usage, respectively; $\zeta_i$, $\lambda_i$, and $\psi_i$ are parameters to be estimated; $\omega_i$ is an error term.

## 4 Results and discussion

### 4.1 Summary of descriptive statistics

The descriptive statistics of the sampled soybean households is presented in Table 1. Results show that the average ages of the respondents were 46.20 ± years. This implies that the majority of the farmers are in their active age and are vibrant and productive. The majority (75.42%) of the farmers were married. Thus, the use of family labor for soybean production might be possible. Approximately 50.63% of the sampled respondents were male, indicating that soybean production is almost equally distributed among the two genders in terms of its production. The average years of education of the farmers were 7.346 ± 3.21 years. This implies that a considerable proportion of soybean farmers are literate and can read and write. The average household size is 7.24 persons for the households. Farm experience indicates that the average years into soybean production were 19.972 ± 13.746 years. This shows that the farmers had been in soybean production for a long period of time and must have accumulated experience over the years. Membership of association result also indicates that approximately 44.16% of the respondents belong to associations. Being a member of associations including farmers' cooperative societies in rural dwellings are important forms of social networks that help farmers obtain outside information about new technologies and innovations and also provide different forms of support to help farmers increase their farm output. The average land cultivated by the farmers indicates that sampled soybean farmers were predominant smallholder farmers in the region. The majority (79.2%) of the respondents do not have access to credit, indicating that the soybean farmers lack financial supports. The average quantity of credit (12324.896 Naira) for farmers that had access to credit is very low, and it shows that farmers were faced with a capital deficit during the planting season thus responsible for the small area of land for soybean

TABLE 1 Summary of descriptive statistics.

| Variable | Mean | Std. dev. | Max. | Min. |
|---|---|---|---|---|
| Age (years) | 46.20 | 15.58 | 18 | 80 |
| Marital status (married) | 0.7542 | 0.4275 | 4 | 1 |
| Gender | 0.5063 | 0.500 | 1 | 0 |
| Years of education | 7.346 | 3.21 | 8 | 0 |
| Household size | 7.245 | 3.584 | 14 | 1 |
| Farm experience (years) | 19.972 | 13.746 | 53 | 6 |
| Membership of association (%) | 0.4416 | 0.4971 | 1 | 0 |
| Access to extension services | 0.7313 | 0.4437 | 1 | 0 |
| Frequency of extension contact (#) | 6.908 | 12.592 | 15 | 0 |
| Access to credit (yes = 1, no = 0) | 0.792 | 0.6472 | 1 | 0 |
| Amount of credit obtained (Naira) | 12324.896 | 15706.13 | 25,000 | 0 |
| Land size cultivated (ha) | 1.8716 | 0.5583 | 2.937 | 0.0625 |
| Years stayed in community | 29.79 | 16.93 | 75 | 2.2 |
| Owned_land (%) | 0.7646 | 0.4785 | 1 | 0 |
| Distance to seed market (km) | 5.03 | 4.710 | 16 | 0 |
| Distance to extension service (km) | 2.892 | 2.176 | 15 | 0.1 |
| Distance to input dealer (km) | 0.979 | 2.713 | 15 | 0 |
| Moro_LGA_Kwara (%) | 0.2437 | 0.4297 | 1 | 0 |
| Ilorin East_LGA_Kwara (%) | 0.3979 | 0.4899 | 1 | 0 |
| Konshisha_LGA_Benue | 0.3270 | 0.4696 | 1 | 0 |
| Vandeikya_LGA_Benue | 0.3346 | 0.4728 | 1 | 0 |

cultivation. The average number of years the respondents had stayed in their community was 29.79 ± 16.93 years. The majority (76.46%) of the respondents owned their farmland and thus were not faced with the problem of land tenure security. The average distance to the seed market and input dealer market was 5.03 ± 4.71 km and 0.97.9 ± 2.71 km, respectively, while the average distance to the nearest extension service was 2.89 ± 2.17 km. The long distance to the nearest seed or input dealer market might affect the adoption of technologies such as ISVs and rhizobium inoculants. The result of the descriptive statistics agrees with Kolapo and Kolapo (2021) and Ojo et al. (2021).

## 4.2 Result of the recursive bivariate probit model

Table 2 shows the RBP model's coefficient estimations. Equations 2, 3 are jointly estimated by the RBP model, as was previously explained. According to Addai et al. (2022) and Li et al. (2021), the results in the lower section of Table 2 indicate that the estimated correlation coefficient $\rho\tau\varepsilon$ is statistically significant and negative, implying the existence of negative selection bias resulting from unobserved factors. The observed negative selection bias is an indication that farmers who are less likely to adopt improved soybean varieties are also less likely to use rhizobia inoculant as a complementary package to increase soybean productivity. These results imply that the influence of adopting improved soybean varieties on the uptake of rhizobium inoculants would be underestimated if selection bias issues were not taken into consideration. Additionally, the statistically significance of the Wald test of $\rho\tau\varepsilon = 0$, which indicates that the null hypothesis—that there is no association between the selection and outcome equations—can be rejected. The result suggests that estimating the improved soybean varieties adoption equation and the rhizobium inoculant usage equation together is preferable to doing it separately. To further understand the factors influencing the adoption of improved soybean varieties and the usage of rhizobium inoculants, we compute the marginal effects of the explanatory variables and report the findings in Table 2. This is necessary as the coefficient estimates of the RBP model are not straightforwardly explained.

### 4.2.1 Determinants of improved soybean varieties adoption

The second column of Table 2 reveals the results for the factor that influences improved soybean adoption. The marginal effect of the age variable is positive and statistically significant indicating that compared with younger farmers, older farmers are 29.8% more likely to adopt improved soybean varieties. Older farmers are expected to have accumulated experiences over the years and might be risk averse; thus, they might be interested in trying new technology. Our result is similar to that of Kolapo et al. (2023) who find that older farmers adopt drought-tolerant maize varieties in Nigeria. The positive significant marginal effect of marital status implies that compared to single or divorced households, married households are 57.1% more likely to adopt improved soybean varieties. Married households with medium to large family sizes could offer extra farm labor in

TABLE 2 Parameter estimates of the recursive bivariate probit model (RBP).

| | RBP model | | Simple probit |
|---|---|---|---|
| Variables | Adoption of ISVs | Adoption of rhizobium inoculants | Adoption of rhizobium inoculants |
| Adoption of ISVs | | 0.2521***(0.0585) | 0.06218***(0.0018) |
| Age | 0.2987***(0.0906) | 5.6205***(0.0863) | 4.7080***(0.4333) |
| Marital status | 0.5714***(0.0580) | 4.1277(5.6821) | 0.0001(0.0006) |
| Gender | 0.6795***(0.0062) | 0.0725***(0.0134) | 0.0005(0.0003) |
| Years of education | 0.2647(0.2099) | 0.0005(0.0004) | 0.0003(0.0003) |
| Household size | 0.0025(0.1729) | 0.0005(0.0006) | −0.0002(0.0003) |
| Farm experience | 0.0005(0.0004) | 0.0002(0.0002) | 0.0003(0.0002) |
| Membership of association | 0.0001(0.0005) | 0.0001(0.0006) | 0.0001(0.0001) |
| Access to extension services | 0.0015***(0.0006) | 0.0114(0.0203) | −0.0006(0.0008) |
| Frequency of extension contact | −0.0004(0.0005) | 0.0264(0.0266) | 0.0003***(0.0001) |
| Access to credit | 0.0 124(0.0 184) | 0.0012***(0.0004) | 0.0031**(0.0017) |
| Amount of credit obtained | 0.1894***(0.0684) | 0.0024***(0.0007) | 0.0018***(0.0005) |
| Land size cultivated | 2.2385***(0.0809) | −0.0004**(0.0002) | 0.0070***(0.0020) |
| Years stayed in community | 1.2451***(0.45 18) | 0.0005(0.0004) | 0.00 16*(0.0009) |
| Owned_land | −0.0009(0.0007) | 0.0005(0.0006) | 0.0002(0.0004) |
| Distance to seed market | 0.0001(0.0001) | 0.0002(0.0002) | 0.0020***(0.0006) |
| Distance to extension service (km) | 0.0002(0.0002) | 0.0025(0.1729) | 0.00013***(0.0004) |
| Distance to input dealer (km) | 0.0035*(0.0021) | 0.0005(0.0004) | 0.0018***(0.0005) |
| Moro_LGA_Kwara | 0.1573***(0.0006) | 0.0001(0.0005) | 0.0070***(0.0020) |
| Konshisha_LGA_Benue | −0.0004(0.0005) | 0.0001(0.0806) | 0.0016*(0.0009) |
| Awareness of ISVs | 0.0035*(0.0021) | | 0.0002(0.0002) |
| Awareness of rhizobium inoculants | | 0.0004(0.0006) | 0.0001(0.0006) |
| Constant | 0.0001(0.0005) | 0.0725***(0.0134) | 0.0001(0.0006) |
| $\rho_{\tau\varepsilon}$ | −1.2451***(0.4518) | | |
| Wald test of $\rho_{\tau\varepsilon} = 0$ | 15.356 | | |
| Prob >$\chi$2 | 0.00036 | | |
| Observation | 480 | | |

Robust standard errors are in parentheses. In Kwara State, the reference region is Ilorin East_LGA while in Benue State, the reference region is Vandeikya_LGA_Benue. ISVs, improved soybean varieties. *$p < 0.1$. **$p < 0.05$. ***$p < 0.01$.

implementing new technology on their farm. In addition, any member of the large household might have gotten information about the existence of improved soybean varieties and might have influenced his/her household to try the new technology. The positive association between household size and improved technology adoption has been previously found in literature (Ojo et al., 2020; Ojo et al., 2021).

Gender has a positive and statistically significant coefficient implying that compared with their female counterparts, male farmers are 67.9% more likely to adopt improved soybean varieties. In Nigeria, male farmers have more access to resources including farm inputs such as land, new technology, labor, and credit facilities. This might have been responsible for this observed result. In addition, some cultures and traditions especially in Northern Nigeria insinuate that when a new program/technology is being introduced to a community, the male farmers should always be in a pole position to attend such programs, hence giving men more priority in terms of access to new innovation in such regions. Our result is consistent with the findings of Kolapo and Kolapo (2023) who find that male farmers adopted more conservation agricultural practices in Nigeria.

Access to extension services is also highly positively associated with the adoption of improved soybean varieties. Having access to extension services helps the farmers to have access to up-to-date information regarding agricultural production. It implies that farmers have a medium for dissemination of information that can encourage farmers to assess current knowledge on new innovations, programs, and farm inputs. This result agrees with Kaila and Tarp (2019) and Zhang et al. (2016), who opined that extension services help farmers improve farm productivity by disseminating agriculture-related information. The amount of credit obtained also has a positive high association with the adoption of improved soybean varieties. This suggests that the size of credit available to the farmers will increase the likelihood of adoption of improved soybean varieties by approximately 18.8%. Having access to financial support affords the farmers the opportunity to purchase farm inputs such as improved seeds and complementary inputs such as pesticides and herbicides. This result is in consonance with that of Kolapo et al. (2023) who found that credit access helps farmers to adopt drought-tolerant maize varieties. Ma et al. (2020) also found that credit accessibility helps farmers adopt ICTs in China.

We show that farm size increases the likelihood of adoption of improved soybean varieties. Farmers with large farm size are more likely to adopt improved technologies such as ISVs because they have extra land to try the new technology before full implementation. Studies (Obayelu et al., 2019; Simtowe et al., 2019) have also shown that farmers with large farm size are sometimes the early adopters because they have a medium for field trials. Number of years positively and significantly associated with the adoption of improved soybean varieties. In the survey region, it is traditional to them that older people who have been in the communities for a long period of time are regarded as elders in the communities, and as such, they are the first point of contact when new programs or innovations are being brought to the communities. This gives them the leverage to be the early adopters of new technologies such as improved soybean varieties in their communities. This result agrees with Kolapo et al. (2022) who found that elders in the communities adopted land management practices earlier because they obtained early information before other community members.

Distance to input dealers has a positive and statistically significant marginal effect. This implies that the closer the distance of the input dealer to the farmers' house stead, the more likely they are to purchase farm inputs including new technologies. Many smallholder farmers lack access to quality infrastructure such as a good roads network; hence, they may face difficulty in transporting themselves on a long-distance input market. Being closer to the input dealer might also afford them the opportunity to have access to timely information regarding new technologies, as the input dealer might frequently inform the farmers of recent and newly released farming technologies that will help the farmers to increase their farm productivity. Furthermore, farmers in Moro LGA of Kwara State are 15.7% more likely to adopt improved soybean varieties than farmers in Ilorin East LGA (reference group). This result underscores the importance of intervention projects in communities as farmers who participated in government or non-governmental programs are more likely to be informed of new technologies, thus influencing their decision to adopt the technologies.

In particular in our result is the positive significance of our instrumental variable. Awareness of the existence of the technology has a positive statistically significant marginal coefficient. This implies that being aware of ISVs increases the likelihood of adoption of improved soybean varieties among farmers. They could have obtained the information from extension agents and input dealers or through community-driven implemented projects. The implication of these results could be traceable to the importance and uniqueness of the chosen instrumental variable for the study. The result agrees with Kolapo and Kolapo (2021) who posited that awareness plays a significant role in farmers' uptake of new technology in Nigeria.

### 4.2.2 Determinants of rhizobium inoculant adoption

The third column of Table 2 indicates the findings for the factors influencing the use of complementary package such as rhizobium inoculants. The adoption of improved soybean varieties improves the likelihood of using rhizobium inoculants by 25.2%. This finding agrees with Ishaq et al. (2022) who concluded in their field experiment that the use of improved soybean varieties should be complemented with rhizobium inoculants to obtain maximum soybean yield.

We also use the conventional probit model to evaluate the influence of the adoption of improved soybean varieties on the usage of rhizobium inoculants for comparative analysis. The results are shown in the final column of Table 2. The findings indicate that the possibility of using rhizobium inoculants as complementary package is increased by 6.2% by improved soybean varieties use, a much smaller increase than that seen in the RBP model. The reason for this is that, although we detect selection bias resulting from factors that are not observed, the basic probit model treats all explanatory variables as exogenous variables (see significant $\rho\tau\varepsilon$ in the lower half of Table 2). As a result, the results from the RBP model estimation are more dependable.

The highly significant positive marginal effect of age indicates a strong association between age and the likelihood of adoption of rhizobium inoculants among soybean farmers. We show that older farmers are more likely to use complementary package such as rhizobium inoculants. This linear relationship might be attributed to experiences accrued by the soybean farmers over the years. They might have observed the differences in yield with non-use of complementary package over the years, thus influencing their decision to use rhizobium inoculants to increase soybean yield. Our result is similar to Wei et al. (2023) who found that long fertilization of farms with rhizobium inoculation helps improve soil quality while increasing soybean yield. The positive and highly significant marginal effect of the gender variable indicates that male farmers are more likely to use rhizobium inoculant. This is expected since from our previous discussion, male farmers are more likely to adopt improved soybean varieties; hence, the use of complementary package such as rhizobium inoculants is expected to be more common among male farmers.

The marginal effect of access to credit and the amount of credit available to farmers were positive and statistically significant, suggesting that farmers with access to credit and a considerable amount of credit are 0.1 and 0.2% more likely to use rhizobium inoculants, respectively. Farmers with adequate financial support have the resources to acquire the soybean complementary package as previously observed for the adoption of improved soybean varieties. Coincidentally, the marginal effect of land size is negative and statistically significant indicating that farmers with large farm size might not adopt rhizobium inoculants. This might be attributed to the fact that farmers with large farm size might have the orientation of increasing crop yield through land expansion because they have access to large farmland. Contrarily, farmers with small farm size on the other hand would be more resource conservative; hence, they will see the need to use land-enhancing technology such as rhizobium inoculants to help them improve the soil fertility of their small farmland. Our finding agrees with Danso-Abbeam and Baiyegunhi that the choice of the use of agrochemicals among cocoa farmers in Ghana is influenced by the size of the farmland.

## 4.3 Heterogeneity analysis of effects of improved soybean adoption based on geographic disaggregated data

We further break down the impact of the adoption of improved soybean varieties on the usage of rhizobium inoculants by geographic region in order to have a better understanding of the heterogeneous impacts of ISVs (Table 3). The marginal effects of other control variables are not shown for simplicity's sake.

When it comes to the regionally disaggregated effects, we discover that adoption of improved soybean varieties raises the likelihood that rural farmers in Moro and Ilorin East LGA's of Kwara State will be able to use rhizobium inoculants by 66.1 and 33.7%, respectively. While in Benue State, rural farmers in Konshisha and Vandeikya LGAs will be able to use rhizobium inoculants by 76 and 24.7%. This result underscores the importance of location variables in the adoption of improved technologies. Farmers located in areas where new technologies were disseminated are more likely to adopt the technologies early. In this study, the surveyed LGAs are known for large production of soybeans in Kwara and Benue States. Hence, the adoption of improved soybean varieties and their complementary package (rhizobium inoculant) might be common in these local government areas.

## 4.4 Joint effects of adoption of improved soybean varieties and rhizobium inoculants adoption on soybean yield and farm income

The combined impacts of rhizobium inoculant usage and adoption of improved soybean varieties on soybean yield and income are shown in Table 4. As previously mentioned, Equation 4 is estimated using the selectivity-corrected OLS model, and endogeneity concerns are controlled for using the adoption variable of predicted improved soybean varieties and the variable of predicted rhizobium inoculant from the SUBP model estimates. The results of the selectivity-corrected OLS model estimation are shown in the second and third columns of Table 4. We observe that soybean yield and farm income are positively and statistically significantly impacted by the adoption of ISVs.

Furthermore, the adoption of rhizobium inoculants shows a positive and statistically significant effect on the yield and income generated from soybean production. This implies that farmers' use of rhizobium inoculants helps them increase their farm yield while also affecting their income positively. Previous studies (Adeyeye et al., 2017; Mabrouk and Belhadj, 2012; Heerwaardena et al., 2018; Mathenge et al., 2019; Ishaq et al., 2022; Wei et al., 2023) have shown that using rhizobium inoculants increases the yield of soybean. Thus, efforts to increase the use of this technology through awareness creation should be promoted among farmers.

TABLE 3 Disaggregated marginal effects of the adoption of ISVs on rhizobium inoculants by geographical location.

| Geographical location | Coefficient | Std. err |
|---|---|---|
| Moro_LGA_Kwara | 0.6612*** | 0.0907 |
| Ilorin East_LGA_Kwara | 0.3379*** | 0.08 L4 |
| Konshisha_LGA_Benue | 0.7601* | 0.4250 |
| Vandeikya_LGA_Benue | 0.2477*** | 0.0942 |
| Control variables | Yes | Yes |

ISVs, improved soybean varieties; $^{*}p < 0.1$. $^{***}p < 0.01$.

Among other factors, we find that the age variable is positive and statistically significant with soybean yield. This indicates that older farmers generated more soybean yield when compared with their younger counterparts. Older farmers are more experienced when it comes to crop production due to their long years of involvement in crop production. They might have accumulated skills through training and seminars and have access to good agronomic practices through their social networks. All this is expected to help them use good agricultural practices such as new technologies that will increase their farm yield. Ojo et al. (2021) found a similar result among rice farmers in south-west Nigeria where they demonstrated that older farmers were more productive than younger ones because of their early uptake of climate adaptation technologies.

Our results indicate that while marital status was positively and significantly associated with the yield and income of the farmers, variable household size also had a positive and significant association with the income of the farmers. Being married contributes to large household size; hence, the household would be provided with more options for farm labor. More hands for farming activities imply more farmland cultivation, which is expected to lead to increased yield and income for the farmers. These results agree with that of Wossen et al. (2017) and Baiyegunhi et al. (2022).

Access to credit and size of credit variables were positive and showed statistically significant relationship with soybean yield. This reveals that credit facilities help farmers increase their farm yield. With access to a considerable amount of credit, farmers have the resources to purchase farm inputs such as improved soybean varieties and complimentary packages such as rhizobium inoculant. This is expected to directly increase their yield keeping other variables of production constant. These findings agree with previous studies (Kolapo et al., 2023; Baiyegunhi et al., 2022) that showed a positive association between access to credit and increased crop yield.

We observed that farmers' location in Moro LGA of Kwara State had a positive association with soybean yield. The reasons for this might be unconnected with the fact that community-driven developmental projects might have been implemented in this area where farmers might have had access to improved seedlings and complimentary packages such as rhizobium inoculant. These areas are also known for the high production of soybeans in the state; hence, farmers might be exchanging ideas on how to better increase their farm yield. Previous studies have shown the importance of location variables in increasing farm yield. They insinuated that the location of the farmers plays a significant role in farm yield increase as farmers that are better positioned in good and easily accessible areas or that are closer to research institutes have a better chance of being disseminated to new technological advancements in agricultural production.

## 4.5 Robustness check [unconditional quantile regression (UQR) estimations]

To provide more insights into our study, we carried out a robustness check using unconditional quantile regression estimated at the 15th, 30th, 45th, 60th, and 75th quantiles to show how joint adoption of improved soybean varieties and rhizobium inoculants affects yield and income distribution of the farmers, respectively. Prior research has utilized both conditional quantile regression (CQR) and unconditioned

TABLE 4 Parameter estimates of the selectivity-corrected OLS (yield and income).

| Variables | Selectivity-corrected OLS Yield (kg/ha) | | Selectivity-corrected OLS Income (Naira/ha) | |
|---|---|---|---|---|
| | Coefficient | Std. err. | Coefficient | Std. err. |
| Adoption of ISVs (predicted) | 0.0633** | 0.0303 | 0.0035*** | 0.0991 |
| Rhizobium inoculant adoption (predicted) | 0.0451* | 0.0022 | 0.0923*** | 0.0252 |
| Age (years) | 0.0418* | 0.0242 | 0.0204 | 0.0126 |
| Marital status | 0.0289*** | 0.0106 | 0.7809*** | 0.1491 |
| Gender | 0.0158 | 0.0192 | 0.0119 | 0.0142 |
| Years of education | 0.0110 | 0.0834 | 0.0151 | 0.0141 |
| Household size | −0.0978 | 0.0140 | 0.0757*** | 0.0126 |
| Farm experience (years) | 0.0922 | 0.0994 | 0.3352 | 0.0940 |
| Membership of association | −0.0215 | 0.0169 | −0.0397 | 0.0028 |
| Access to extension services | 0.0561 | 0.0140 | 0.0140 | 0.1252 |
| Frequency of ext. contact (#) | 0.0626 | 0.0155 | −0.0923 | 0.0989 |
| Access to credit | 0.0140* | 0.0078 | −0.0397 | 0.0286 |
| Amount of credit obtained | 0.0102** | 0.0446 | −0.0175 | 0.0239 |
| Land size cultivated (ha) | −0.0895 | 0.0862 | 0.0111 | 0.0983 |
| Years stayed in community | 0.0479 | 0.0317 | −0.0454 | 0.0365 |
| Owned_land (%) | 0.0134 | 0.0119 | −0.0175 | 0.0239 |
| Distance to seed market (km) | 0.0003 | 0.0039 | 0.0533 | 0.1227 |
| Distance to extension service (km) | −0.0100 | 0.0069 | 0.0104 | 0.0142 |
| Distance to input dealer (km) | 0.0032 | 0.0064 | 0.0326 | 0.0329 |
| Moro_LGA_Kwara (%) | 0.2177*** | 0.0812 | −0.0039 | 0.0252 |
| Konshisha_LGA_Benue | −0.0504 | 0.1204 | 0.5804 | 0. 3,616 |
| Constant | −1.70E-07 | 2.55E-07 | −0.3338 | 0.4181 |
| $\rho_{\tau\varepsilon}$ | −0.0098*** (0.0014) | | | |
| Wald test of $\rho_{\tau\varepsilon} = 0$ | 4.173 | | | |
| Prob >χ2 | 0.0049 | | | |
| Observation | 480 | | | |

In Kwara State, the reference region is Ilorin East_LGA while in Benue State, the reference region is Vandeikya_LGA_Benue. ISV's, improved soybean varieties. *$p < 0.1$. **$p < 0.05$. ***$p < 0.01$.

quantile regression (UQR) models (Gregory and Zierahn, 2022; Ma and Zheng, 2022). In contrast to the CQR model, which defines its quantiles based on the chosen covariates, we can freely add or remove covariates from the UQR model without changing the quantile definitions. Consequently, we use the UQR model for empirical reasons in our study and the results are presented in Table 5.

The findings demonstrate the heterogeneous effects of the adoption of rhizobium inoculants and improved soybean varieties on soybean yield and farm income. The adoption of improved soybean varieties has a positive and significant impact on yield per ha except at the 15th quantile that is not significant. At the chosen quantiles, the estimated effects increase monotonically, with the highest positive effect happening at the 60th quantile. The use of rhizobium inoculants as complementary technology affects soybean yield positively and significantly with the estimated effects being largest at the 75th quantile except the 45th quantile that is not significant. Our findings suggest that farmers with large farm size often gain more from improved soybean varieties and rhizobium inoculant adoption than their counterparts with small farm size.

With respect to farm income, our findings also demonstrate the heterogeneous effects of rhizobium inoculants and the adoption of improved soybean varieties on farmers' income. The adoption of improved soybean varieties has a positive and significant impact on income per hectare except at the 30th and 45th quantiles that are not significant. At the chosen quantiles, the estimated effects have the highest positive effect happening at the 75th quantile. The use of rhizobium inoculants as complementary technology affects farm income positively and significantly with the estimated effects also being largest at the 75th quantile except the 15th and 60th quantiles that were not significant. Our findings suggest that wealthy farmers or farmers with access to credit often gain more from improved soybean varieties rhizobium inoculant adoption than their poor counterparts because of their ability to acquire improved soybean varieties using rhizobium inoculant technologies.

10.3389/fsufs.2025.1509230

TABLE 5 Parameter estimates of UQR.

| Variables | Selected quantiles (Dependent variable = soybean yield) | | | | | Selected quantiles (Dependent variable = farm income) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Yield (kg/ha) | | | | | Income (Naira/ha) | | | | |
| | 15th | 30th | 45th | 60th | 75th | 15th | 30th | 45th | 60th | 75th |
| Adoption of ISVs (predicted) | 0.395(0.095) | 0.280***(0.149) | 0.0689***(0.0002) | 0.799*** (0.004) | 0.236***(0.047) | 0.221***(0.059) | 0.403(0.123) | 0.514(0.434) | 0.403***(0.123) | 0.647***(0.094) |
| Rhizobium inoculant adoption (predicted) | 0.147***(0.031) | 0.236***(0.047) | 0.047(0.031) | 0.539*** (0.034) | 0.629***(0.059) | 0.059(0.0 18) | 0.237***(0.081) | 0.431***(0.190) | 0.0001 (0.0001) | 0.533***(0.067) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Constant | 0.237***(0.081) | 2.390***(0.114) | 5.553***(0.756) | 3.323**(1.716) | 8.890***(1.332) | 2.401***(0.986) | 3.592***(0.693) | 2.067**(0.986) | 4.147***(1.39) | 11.088***(2.443) |
| Observation | 480 | 480 | 480 | 480 | 480 | 480 | 480 | 480 | 480 | 480 |

Robust standard errors are in parentheses. Soybean yield in kg/ha and income in naira/ha. ISVs—Improved soybean varieties; UQR, unconditional quantile regression. $^{**}p < 0.05$. $^{***}p < 0.01$.

# 5 Conclusion

Using household-level data from North Central Nigeria, this study examines the effect of the adoption of improved soybean varieties on the usage of rhizobium inoculants and the joint effects of improved soybean varieties adoption and use of rhizobium inoculants on soybean yield and farm income. As both observed and unobserved factors may affect farmers' decisions to become improved soybean varieties adopters or non-adopters, an RBP model is used to address the selection bias issue associated with the adoption of improved soybean varieties. Furthermore, a selectivity-corrected OLS model is applied to estimate the joint effects of the adoption of improved soybean varieties adoption and the usage of rhizobium inoculants on soybean yield and farm income. The results of the RBP model reveal a negative selection bias due to unobserved factors. After controlling for this selection bias, we show that the adoption of improved soybean varieties increases the probability of using rhizobium inoculants by 25.2% as a complementary technological package. In addition to the adoption of improved soybean varieties, we found age, gender, access to credit, amount of credit, and farm size all influenced farmers' decision to use rhizobium inoculant. For improved soybean varieties adoption, variables such as age, marital status, gender, access to extension services, amount of credit obtained, farm size, years stayed in community, distance to input market, being located in Moro LGA in Kwara State and awareness of ISVs affected farmers' decision to adopt improved soybean varieties. The disaggregated analyses reveal that the effects of the adoption of improved soybean varieties on the use of rhizobium inoculants are heterogeneous between geographical locations. We observe that soybean yield and farm income are positively and statistically significantly impacted by the adoption of ISVs. Furthermore, the adoption of rhizobium inoculants shows a positive and statistically significant effect on the yield and income generated from soybean production. This implies that farmers' use of rhizobium inoculants helps them increase their farm yield while also affecting their income positively. To provide more insights into our study, we carried out a robustness check using unconditional quantile regression to show how joint adoption of improved soybean varieties and rhizobium inoculants affects yield and income distribution of the farmers, respectively. The findings demonstrate the heterogeneous effects of rhizobium inoculants and the adoption of improved soybean varieties on soybean yield and farm income. Findings from this study can be generalized to other regions with similar agroecological conditions because Kwara and Benue States feature agroecological zones characterized by similar climatic conditions, soil types, and farming systems to other regions within the Guinea Savannah and Sudan Savannah zones. These zones span across Nigeria and into neighboring West African countries such as Ghana, Cameroon, and parts of Niger. In addition, smallholder farming systems dominate not only Kwara and Benue but also many other areas in West Africa. Farmers face similar constraints, such as limited access to extension services, input markets, and credit, as well as reliance on traditional farming practices.

# 6 Policy recommendations

Our finding generally confirms the significant role of the adoption of improved soybean varieties in facilitating farmers' use of rhizobium inoculant as a complementary package. This suggests that the international and local research institutes, both government and non-government organizations and stakeholders, should make further efforts to increase awareness creation about the usefulness of recent advancements in agricultural technologies such as improved soybean varieties and rhizobium inoculant and improve the poor's access to credit. As the crop production sectors are gender-sensitive, developing programs and interventions should consider gendered differences in improved technology dissemination. When putting intervention strategies for better technology dissemination into practice, rural women should receive extra consideration. Our findings suggest that the government should assist in providing direct financial subsidies to farmers for purchasing improved soybean varieties and rhizobium inoculants. This can offset initial costs and encourage adoption. Policymakers should strengthen extension services to educate farmers about the benefits of improved varieties and rhizobium inoculants and provide practical training on their application and management.

## 7 Limitations of the study

We are unable to capture the dynamic relationships between improved soybean varieties, rhizobium inoculant, soybean yield, and farm revenue as our empirical analyses are based on 1-year cross-sectional data. However, we think these are interesting topics for further investigation once the data needed are accessible.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

AK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. TO: Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. NK: Investigation, Methodology, Project administration, Resources, Writing – review & editing. KE: Investigation, Methodology, Project administration, Resources, Writing – review & editing. HK: Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing – review & editing. OF: Investigation, Methodology, Project administration, Resources, Writing – review & editing.

## Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This research was supported by The Researchers Supporting Project number (RSPD2025R952), King Saud University, Riyadh, Saudi Arabia.

## Conflict of interest

The 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 authors declare that no Generative AI was used in the creation of this manuscript.

## Publisher's note



## References

Abd-Alla, M., El-Enany, A., Nafady, N., Khalaf, D., and Morsy, F. (2014). Synergistic interaction of *Rhizobium leguminosarum* bv. Viciae and arbuscular mycorrhizal fungi as a plant growth promoting biofertilizers for faba bean (*Vicia faba* L.) in alkaline soil. *Microbiol. Res.* 169, 49–58. doi: 10.1016/j.micres.2013.07.007

Abdullahi, A. (2004). Soybean production. Nigeria: Meiden edition, Raw Materials Research and Development Council (RMRDC), 17.

Addai, K. N., Temoso, O., and Ng'ombe, J. N. (2022). Participation in farmer organizations and adoption of farming technologies among rice farmers in Ghana. *Int. J. Soc. Econ.* 49, 529–545. doi: 10.1108/IJSE-06-2021-0337

Adeyeye, A. S., Togun, A. O., Olaniyan, A. B., and Akanbi, W. B. (2017). Effect of fertilizer and Rhizobium inoculation on growth and yield of Soyabean variety (*Glycine max* L Merrill). *Adv Crop Sci Tech* 5:255. doi: 10.4172/2329-8863.1000255

Ahemad, M., and Kibret, M. (2014). Mechanisms and applications of plant growth promoting rhizobacteria: current perspective. *J. King. Saud. Univ. Sci.* 26, 1–20. doi: 10.1016/j.jksus.2013.05.001

Ahmad, W., Singh, B., Dijkstra, F., and Dalal, R. (2013). Inorganic and organic carbon dynamics in a limed acid soil are mediated by plants. *Soil. Boil. Biochem.* 57, 549–555. doi: 10.1016/j.soilbio.2012.10.013

Amesimeku, J., and Anang, B. T. (2021). Profit efficiency of smallholder soybean farmers in Tolon District of northern region of Ghana. *Ghana J. Sci. Technol. Develop.* 7, 29–43.

Baiyegunhi, L. J. S., Akinbosoye, F., and Bello, L. O. (2022). Welfare impact of improved maize varieties adoption and crop diversification practices among smallholder maize farmers in Ogun state, Nigeria. *Heliyon* 8:e09338. doi: 10.1016/j.heliyon.2022.e09338

Balogun, T. F. (2009). An Integrated Remote Sensing and GIS Approach in Monitoring Urban Expansion: A Case Study of Benin City, Nigeria. *M.Sc. Thesis, Department of Geography and Planning Science, Faculty of Social and Management Science*, Adekunle Ajasin University.

Barbosa, J., Hungria, M., Sena, J., Poggere, G., dos Reis, A., and Corrêa, R. (2021). Meta-analysis reveals benefits of co-inoculation of soybean with *Azospirillum brasilense* and *Bradyrhizobium* spp. *Brazil. Appl. Soil. Ecol.* 163:103913. doi: 10.1016/j.apsoil.2021.103913

Castro, J., Calijuri, M., Ferreira, J., Assemany, P., and Ribeiro, V. (2020). Microalgae based biofertilizer: a life cycle approach. *Sci. Total Environ.* 724:138138. doi: 10.1016/j.scitotenv.2020.138138

Cochran, W. G. (1977). *Sampling Techniques*. 3rd Edition, John Wiley & Sons, New York.

Dai, X., Zhou, W., Liu, G., Liang, G., He, P., and Liu, Z. (2019). Soil C/N and pH together as a comprehensive indicator for evaluating the effects of organic substitution management in subtropical paddy fields after application of high-quality amendments. *Geoderma* 337, 1116–1125. doi: 10.1016/j.geoderma.2018.11.023

Drijber, R., Doran, J., Parkhurst, A., and Lyon, D. (2000). Changes in soil microbial community structure with tillage under long-term wheat-fallow management. *Soil. Boil. Biochem.* 32, 1419–1430. doi: 10.1016/s0038-0717(00)00060-2

Dugje, I. Y., Omoigui, L. O., Ekeleme, F., Bandyopadhyay, R., Kumar, L., and Kamara, A. Y. (2009). Farmers' Guide to Soybean Production in Northern Nigeria. *International institute of Tropical Agriculture*. Nigeria, 21 pp.

Ewansiha, S. U., Oghenebrume, K. E., Aigbe, U. D., and Osaigbovo, A. U. (2022). Nodulation, dry matter accumulation and yields of soybean (Glycine max L.) cultivars at varying plant spacing in a rainforest agro-ecology. *Agro-Science*, 21, 45–52.

FAOSTAT. (2021). Food and agriculture organization of the United Nations. Production dataset. Available at: http://faostat3.fao.2021. (Accessed, Decemebr 09, 2023).

Gregory, T., and Zierahn, U. (2022). When the minimum wage really bites hard: the negative spillover effect on high-skilled workers. *J. Public Econ.* 206:104582. doi: 10.1016/j.jpubeco.2021.104582

Haddabi, A. S. (2020). Promotion of integrated Pest management (IPM) in cowpea production in Fufore local government area, Adamawa state, Nigeria. *Int. J. Engin. Technol. Manage. Res.* 7, 11–40. doi: 10.29121/ijetmr.v7.i6.2020.689

Han, Q., Ma, Q., Chen, Y., Tian, B., Xu, L., Bai, Y., et al. (2020). Variation in rhizosphere microbial communities and its association with the symbiotic efficiency of rhizobia in soybean. *ISME J.* 14, 1915–1928. doi: 10.1038/s41396-020-0648-9

Heerwaardena, J., Frederick, B., Kyei-Boahen, S., Adjei-Nsiahd, S., Peter, E., Nkeki, K., et al. (2018). Soyabean response to rhizobium inoculation across sub-Saharan Africa: patterns of variation and the role of promiscuity. *Agric. Ecosyst. Environ.* 261, 211–218. doi: 10.1016/j.agee.2017.08.016

Hungria, M., Nogueira, M., and Araujo, R. (2013). Co-inoculation of soybeans and common beans with rhizobia and azospirilla: strategies to improve sustainability. *Biol. Fertil. Soils* 49, 791–801. doi: 10.1007/s00374-012-0771-5

Idrisa, Y. I., Ogunbbameru, N. O., and Amaza, P. S. (2010). Influence of farmers socio-economic and technological characteristics on soybean seed technology adoption in southern Borno state Nigeria. *Agro Sci. J. Tropical Agric. Food Environ. Extension* 9, 209–214.

Igiehon, N., and Babalola, O. (2017). Biofertilizers and sustainable agriculture: exploring arbuscular mycorrhizal fungi. *Appl. Microbiol. Biotechnol.* 101, 4871–4881. doi: 10.1007/s00253-017-8344-z

Ishaq, M., Hayatu, L. A., Sani, and Ahmed, H. (2022). Effect of rhizobia inoculation on growth and yield of selected soybean (*Glycine max* l.) varieties under salt stress. *J. Agric. Environ.* 18, 37–48.

Ji, L., Ni, K., Wu, Z., Zhang, J., Yi, X., Yang, X., et al. (2020). Effect of organic substitution rates on soil quality and fungal community composition in a tea plantation with long-term fertilization. *Biol. Fertil. Soils* 56, 633–646. doi: 10.1007/s00374-020-01439-y

Kaila, H., and Tarp, F. (2019). Can the internet improve agricultural production? Evidence from Viet Nam. *Agric. Econ.* 50, 675–691. doi: 10.1111/agec.12517

Kedi, W. E., Ejimuda, C., Idemudia, C., and Ijomah, T. I. (2024). AI Chatbot integration in SME marketing platforms: Improving customer interaction and service efficiency. *Int. J. Manag. Innov. Entrep. Res.* 6, 2332–2341.

Khalid, M., Liu, X., Ur Rahman, S., Rehman, A., Zhao, C., Li, X., et al. (2023). Responses of microbial communities in rhizocompartments of king grass to phytoremediation of cadmium-contaminated soil. *Sci. Total Environ.* 904:167226. doi: 10.1016/j.scitotenv.2023.167226. Epub 2023 Sep 19

Khalid, M., Rahman, S.u., Liu, X. (2022b). Biochar and organic fertilizer amendments stimulate the dynamics of ammonia oxidizers community in a slightly alkaline soil. *Arab. J. Geosci.* 15:1612. doi: 10.1007/s12517-022-10916-7

Khalid, M., Rahman, S., Liu, X., and Hui, N. (2022a). Exogenous application of glycine and nitrate on antioxidant and polyphenol metabolism in *Brassica campestris* spp Chinensis. *J. Plant Nutr.* 46, 2089–2103. doi: 10.1080/01904167.2022.2120820

Kolapo, A., Didunyemi, A. J., Aniyi, O. J., and Obembe, O. E. (2022). Adoption of multiple sustainable land management practices and its effects on productivity of smallholder maize farmers in Nigeria. *Resources Environ. Sustain.* 10:100084. doi: 10.1016/j.resenv.2022.100084

Kolapo, A., and Kolapo, A. J. (2021). Welfare and productivity impact of adoption of biofortified cassava by smallholder farmers in Nigeria. *Cogent Food Agric.* 7:1886662. doi: 10.1080/23311932.2021.1886662

Kolapo, A., and Kolapo, A. J. (2023). Implementation of conservation agricultural practices as an effective response to mitigate climate change impact and boost crop productivity in Nigeria. *J. Agric. Food Res.* 12, 100557–100559. doi: 10.1016/j.jafr.2023.100557

Kolapo, A., Muhammed, O. A., Kolapo, A. J., Olowolafe, D. E., Eludire, A. I., Didunyemi, A. J., et al. (2023). Adoption of drought tolerant maize varieties and farmers' access to credit in Nigeria: implications on productivity. *Sustain. Fut.* 6, 100142–100112. doi: 10.1016/j.sftr.2023.100142

Kolapo, A., Ologundudu, O. M., and Adekunle, I. A. (2020). Gender, membership in farmers' association and adoption of biofortification in Nigeria: the case of bio-fortified cassava. *SSRG Int. J. Agric. Environ. Sci.* 7, 38–45. doi: 10.14445/23942568/IJAES-V7I3P105

Kolapo, A., Ojo, C. F., Lawal, A. M., Abayomi, T. J., and Muhammed, O. A. (2021a). Sensitivity analysis and future farm size projection of biofortified cassava production in Oyo State, *Nigeria. Malays. J. Sustain. Agric.* 5, 61–66.

Kolapo, A., Raji, I. A., Falana, K., and Muhammed, O. A. (2021b). Farm size efficiency differentials of bio-fortified cassava production in Nigeria: a stochastic frontier analysis approach. *Malays. J. Sustain. Agric.* 5, 51–60.

Korir, H., Mungai, N., Thuita, M., Hamba, Y., and Masso, C. (2017). Co-inoculation effect of rhizobia and plant growth promoting rhizobacteria on common bean growth in a low phosphorus soil. *Front. Plant Sci.* 8:141. doi: 10.3389/fpls.2017.00141

Koskey, G., Mburu, S., Njeru, E., Kimiti, J., Ombori, O., and Maingi, J. (2017). Potential of native rhizobia in enhancing nitrogen fixation and yields of climbing beans (*Phaseolus vulgaris* L.) in contrasting environments of eastern Kenya. *Front. Plant Sci.* 8:443. doi: 10.3389/fpls.2017.00443

Li, C., Cheng, W., and Shi, H. (2021). Early marriage and maternal health care utilisation: Evidence from sub-Saharan Africa. *Econ Hum Biol.* 43:101054. doi: 10.1016/j.ehb.2021.101054

Liu, Y., Guo, Z., and Shi, H. (2022). Rhizobium symbiosis leads to increased drought tolerance in chinese milk vetch (*Astragalus sinicus* L.). *Agronomy* 12:725. doi: 10.3390/agronomy12030725

Lokshin, M., and Sajaia, Z. (2011). Impact of interventions on discrete outcomes: maximum likelihood estimation of the binary choice models with binary endogenous regressors. *Stata J.* 11, 368–385. doi: 10.1177/1536867X1101100303

Ma, W., Grafton, R. Q., and Renwick, A. (2020). Smartphone use and income growth in rural China: empirical results and policy implications. *Electron. Commer. Res.* 20, 713–736. doi: 10.1007/s10660-018-9323-x

Ma, W., Renwick, A., and Grafton, Q. (2018). Farm machinery use, off-farm employment and farm performance in China. *Aust. J. Agric. Resour. Econ.* 62, 279–298. doi: 10.1111/1467-8489.12249

Ma, D., Yin, L., Ju, W., Li, X., Liu, X., Deng, X., et al. (2021). Meta-analysis of green manure effects on soil properties and crop yield in northern China. *Field Crop Res.* 266:108146. doi: 10.1016/j.fcr.2021.108146

Ma, W., and Zheng, H. (2022). Heterogeneous impacts of information technology adoption on pesticide and fertiliser expenditures: evidence from wheat farmers in China*. *Aust. J. Agric. Resour. Econ.* 66, 72–92. doi: 10.1111/1467-8489.12446

Mabrouk, Y., and Belhadj, O. (2012). Enhancing the biological nitrogen fixation of leguminous crops grown under stressed environments. *Afr. J. Biotechnol.* 11, 10809–10815.

Mahama, A., Awuni, J. A., Mabe, F. N., and Azumah, S. B. (2020). Modelling adoption intensity of improved soybean production technologies in Ghana: a generalized Poisson approach. *Heliyon* 6:e03543. doi: 10.1016/j.heliyon.2020.e03543

Maikasuwa, M. A., and Ala, A. L. (2013). Trend analysis of area and productivity of sorghum in Sokoto State, Nigeria, 1993-2012. *Eur. Sci. J.* 9, 1–10.

Marks, B., Megías, M., Ollero, F., Nogueira, M., Araujo, R., and Hungria, M. (2015). Maize growth promotion by inoculation with *Azospirillum brasilense* and metabolites of *Rhizobium tropici* enriched on lipo-chitooligosaccharides (LCOs). *AMB Express* 5:71. doi: 10.1186/s13568-015-0154-z

Mathenge, M. K., Smale, M., and Olwande, J. (2019). The impacts of hybrid maize seed on the welfare of farming households in Kenya. *Food Policy.* 44, 262–271. doi: 10.1016/j.foodpol.2013.09.013

Mehboob, I., Naveed, M., and Zahir, Z. (2009). Rhizobial association with nonlegumes: mechanisms and applications. *Crit. Rev. Plant Sci.* 28, 432–456. doi: 10.1080/07352680903187753

Minah, M. (2022). What is the influence of government programs on farmer organizations and their impacts? Evidence from Zambia. *Ann. Public Cooper. Econ.* 93, 29–53. doi: 10.1111/apce.12316

Moretti, L., Crusciol, C., Bossolani, J., Calonego, J., Moreira, A., Garcia, A., et al. (2021). Beneficial microbial species and metabolites alleviate soybean oxidative damage and increase grain yield during short dry spells. *Eur. J. Agron.* 127:126293. doi: 10.1016/j.eja.2021.126293

Muhammad, U., Iftikhar, H. S., Irfan, A. S., Sanaullah, M., Abdul, R., Ghulam, M., et al. (2024). Synergistic partnerships of endophytic fungi for bioactive compound production and biotic stress management in medicinal plants. *Plant Stress* 11, 1–22.

Nett, R., Bender, K., and Peters, R. (2022). Production of the plant hormone gibberellin by rhizobia increases host legume nodule size. *ISME J.* 16, 1809–1817. doi: 10.1038/s41396-022-01236-5

Nkegbe, P. K., Araar, A., Abu, B. M., Alhassan, H., Ustarz, Y., Setsoafia, E. D., et al. (2022). Nonfarm activity and market participation by farmers in Ghana. *Agric. Food Econ.* 10, 1–23. doi: 10.1186/s40100-022-00210-1

Obayelu, O. A., Fakolujo, O. M., and Awotide, B. A. (2019). What impact does the adoption of drought-tolerant maize for africa have on the yield and poverty status of farmers in the arid region of Nigeria? *J. Agric. Sci.* 64, 303–317. doi: 10.2298/JAS1903303O

Ogunyemi, K. A. O. V., Ologundudu, O. M., Adekunle, I. A., Akinloye, M. O., and Komolehin, F. (2021). Farmers' choice of varieties and demand for improved cassava stems in Nigeria. *Int. J. Agril. Res. Innov. Tech.* 11, 42–51.

Ojo, T. O., Baiyegunhi, L. J. S., and Adetoro Ogundeji, A. A. (2021). Adoption of soil and water conservation technology and its effect on the productivity of smallholder rice farmers in Southwest Nigeria, Heliyon 7 2021, 17. doi: 10.22004/ag.econ.314981

Ojo, T. O., Ogundeji, A. A., Babu, S. C., and Alimi, T. (2020). Estimating Financing Gaps in Rice Production in Southwestern Nigeria. *J. Econ. Struct.* 9, 12.

Omeke, J. O. (2016). Effect of tillage, Rhizobium inoculation in maize-SoybeanBased cropping systems and nitrogen fertilizer application on chemical fertility status of savanna Alfisol, Nigeria. *Agro-Science J. Tropical Agric. Food Environ. Extension* 15, 18–29.

Oyenpemi, L. O., Solaja, S. O., Fadeyi, B. O., Awe, T. E., Ayojimi, W., Etta-Oyong, S. O., et al. (2023). Economic performance of smallholder soya bean production in Kwara state, Nigeria. *Open Agric.* 2023, 1–10.

Pereira, S., Mucha, Â., Gonçalves, B., Bacelar, E., Látr, A., Ferreira, H., et al. (2019). Improvement of some growth and yield parameters of faba bean (*Vicia faba*) by inoculation with Rhizobium laguerreae and arbuscular mycorrhizal fungi. *Crop Pasture Sci.* 70, 595–605. doi: 10.1071/cp19016

Rehman, A., Rahman, S. U., Li, P., Shah, I. H., Manzoor, M. A., Azam, M., et al. (2024). Modulating plant-soil microcosm with green synthesized ZnONPs in arsenic contaminated soil. *J. Hazard. Mater.* 470:134130. doi: 10.1016/j.jhazmat.2024.134130

Ronner, E., Franke, A. C., Vanlauwe, B., Dianda, M., Edeh, E., Ukem, B., et al. (2016). Understanding variability in soybean yield and response to P- fertilizer and rhizobium inoculants on farmers fields in northern Nigeria. *Field Crop Res.* 186, 133–145. doi: 10.1016/j.fcr.2015.10.023

Schütz, L., Gattinger, A., Meier, M., Müller, A., Boller, T., Mäder, P., et al. (2018). Improving crop yield and nutrient use efficiency via biofertilization – a global metaanalysis. *Front. Plant Sci.* 8:2204. doi: 10.3389/fpls.2017.02204

Shimada, G., and Sonobe, T. (2021). Impacts of management training on workers: evidence from Central America and the Caribbean region. *Rev. Dev. Econ.* 25, 1492–1514. doi: 10.1111/rode.12773

Simtowe, T., Amondo, E., Marenyaa, P., Rahut, D., Sonder, K., and Erenstein, O. (2019). Impacts of drought-tolerant maize varieties on productivity, risk, and resource use: evidence from Uganda. *Land Use Policy* 88, 1–16. doi: 10.1016/j.landusepol.2019.104091

Soumare, A., Diedhiou, A., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., et al. (2020). Exploiting biological nitrogen fixation: a route towards a sustainable agriculture. *Plan. Theory* 9:1011. doi: 10.3390/plants9081011

Tafida, I., Nazifi, B., and Adam, A. S. (2022). Socio-economic analysis of the adoption of selected improved soybean (glycine max) varieties in Tofa local government area of Kano state, Nigeria. *FUDMA J. Agric. Agric. Technol.* 8, 99–107. doi: 10.33003/jaat.2022.0801.079

Tesfahunegn, G. B., Mekonen, K., and Tekle, A. (2016). Farmers' perception on causes, indicators and determinants of climate change in northern Ethiopia: implication for developing adaptation strategies. *Appl. Geogr.* 73, 1–12. doi: 10.1016/j.apgeog.2016.05.009

Thilakarathna, M., and Raizada, M. (2017). A meta-analysis of the effectiveness of diverse rhizobia inoculants on soybean traits under field conditions. *Soil. Boil. Biochem.* 105, 177–196. doi: 10.1016/j.soilbio.2016.11.022

Trabelsi, D., and Mhamdi, R. (2013). Microbial inoculants and their impact on soil microbial communities: a review. *Biomed. Res. Int.* 2013:11. doi: 10.1155/2013/863240

Ugbabe, O. O., Abdoulaye, T., Kamara, A., Mbavai, J., and Oyinbo, O. (2017). Profitability and technical efficiency of soybean production in northern Nigeria. *Tropicultura* 35, 203–214.

USAID (2016). Nigeria early generation seed study (EGS): *Country report on early generation seed systems study- feed the future: Building Capacity for African Agricultural Transformation (Africa Lead II)* USAID, 51–53.

Vanlauwe, B., Coe, R. I. C., and Giller, K. E. (2019). Beyond averages: new approaches to understand heterogeneity and risk of technology success or failure in smallholder farming. *Exp. Agric.* 55, 84–106. doi: 10.1017/S0014479716000193

Wei, W., Guan, D., Ma, M., Jiang, X., Fan, F., Meng, F., et al. (2023). Long-term fertilization coupled with rhizobium inoculation promotes soybean yield and alters soil bacterial community composition. *Front. Microbiol.* 14:1161983. doi: 10.3389/fmicb.2023.1161983

Wooldridge, J. (2015). Control function methods in applied econometrics. *J. Hum. Resour.* 50, 420–445. doi: 10.3368/jhr.50.2.420

Wossen, T., Abdoulaye, T., Alene, A., Feleke, S., Menkir, A., and Manyong, V. (2017). Measuring the impacts of adaptation strategies to drought stress: the case of drought tolerant maize varieties. *J. Environ. Manag.* 203, 106–113. doi: 10.1016/j.jenvman.2017.06.058

Wu, S., Cao, Z., Li, Z., Cheung, K., and Wong, M. (2005). Effects of biofertilizer containing N-fixer, P and K solubilizers and AM fungi on maize growth: a greenhouse trial. *Geoderma* 125, 155–166. doi: 10.1016/j.geoderma.2004.07.003

Xiao, Q., Huang, Y., Wu, L., Tian, Y., Wang, Q., Wang, B., et al. (2021). Long-term manuring increases microbial carbon use efficiency and mitigates priming effect via alleviated soil acidification and resource limitation. *Biol. Fertil. Soils* 57, 925–934. doi: 10.1007/s00374-021-01583-z

Xie, S., Yang, F., Feng, H., Yu, Z., Liu, C., Wei, C., et al. (2021). Organic fertilizer reduced carbon and nitrogen in runoff and buffered soil acidification in tea plantations: evidence in nutrient contents and isotope fractionations. *Sci. Total Environ.* 762:143059. doi: 10.1016/j.scitotenv.2020.143059

Yang, X., Ni, K., Shi, Y., Yi, X., Zhang, Q., Fang, L., et al. (2018). Effects of longterm nitrogen application on soil acidification and solution chemistry of a tea plantation in China. *Agric. Ecosyst. Environ.* 252, 74–82. doi: 10.1016/j.agee.2017.10.004

Yanni, Y., Dazzo, F., Squartini, A., Zanardo, M., Zidan, M., and Elsadany, A. (2016). Assessment of the natural endophytic association between Rhizobium and wheat and its ability to increase wheat production in the Nile delta. *Plant Soil* 407, 367–383. doi: 10.1007/s11104-016-2895-0

Zhang, G., Song, K., Miao, X., Huang, Q., Ma, J., Gong, H., et al. (2021). Nitrous oxide emissions, ammonia volatilization, and grain-heavy metal levels during the wheat season: effect of partial organic substitution for chemical fertilizer. *Agric. Ecosyst. Environ.* 311:107340. doi: 10.1016/j.agee.2021.107340

Zhang, Y., Wang, L., and Duan, Y. (2016). Agricultural information dissemination using ICTs: a review and analysis of information dissemination models in China. *Inform. Process. Agric.* 3, 17–29. doi: 10.1016/j.inpa.2015.11.002

Zhang, X., Zhang, R., Gao, J., Wang, X., Fan, F., Ma, X., et al. (2017). Thirty-one years of rice-rice-green manure rotations shape the rhizosphere microbial community and enrich beneficial bacteria. *Soil. Boil. Biochem.* 104, 208–217. doi: 10.1016/j.soilbio.2016.10.023

Zhuang, X., Chen, J., Shim, H., and Bai, Z. (2007). New advances in plant growthpromoting rhizobacteria for bioremediation. *Environ. Int.* 33, 406–413. doi: 10.1016/j.envint.2006.12.005

Zilli, J., Pacheco, R., Gianluppi, V., Smiderle, O., Urquiaga, S., and Hungria, M. (2021). Biological N2 fixation and yield performance of soybean inoculated with Bradyrhizobium. *Nutr. Cycl. Agroecosyst.* 119, 323–336. doi: 10.1007/s10705-021-10128-7