frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 25 September 2025
DOI 10.3389/fsufs.2025.1505454

OPEN ACCESS

EDITED BY
Priscilla Ntuchu Kephe,
Julius Kühn Institute, Germany

REVIEWED BY
Peter Newton,
University of Colorado Boulder, United States
Wonder Agbenyo,
Sichuan Agricultural University, China

*CORRESPONDENCE
Adetomiwa Kolapo
✉ kolapoadetomiwa@gmail.com

RECEIVED 03 October 2024
ACCEPTED 25 August 2025
PUBLISHED 25 September 2025

CITATION
Kolapo A, Tijani AA, Oluwatayo IB, Ojo TO, Khumalo NZ, Elhindi KM, Kassem HS and Adeleye FA (2025) Sustainable intensification of cocoa production under a changing climate in Southwest, Nigeria.
Front. Sustain. Food Syst. 9:1505454.
doi: 10.3389/fsufs.2025.1505454

Sustainable intensification of cocoa production under a changing climate in Southwest, Nigeria

Adetomiwa Kolapo[1]*, Akeem Abiade Tijani[1], Isaac Busayo Oluwatayo[2], Temitope O. Ojo[1,3,4], Nolwazi Z. Khumalo[5], Khalid M. Elhindi[6], Hazem S. Kassem[7] and Feyisayo Adeola Adeleye[1]

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

This study examines the sustainable intensification of cocoa production in Southwest Nigeria, focusing on Ondo State, under the pressures of a changing climate. West Africa dominates global cocoa production, with Nigeria ranking as the fourth-largest producer, yet its yields remain low compared to higher outputs in countries like Côte d'Ivoire. Climate change, coupled with low adoption of intensification technologies and extreme weather events, has contributed to declining productivity in Nigeria. This research investigated the determinants and impacts of adopting intensification technologies, such as improved seedlings, fertilizers, and pesticides, on cocoa yields in Ondo State, a major production hub. Using a multi-stage sampling technique, we collected data from smallholder farmers and analyzed with descriptive statistics, a multinomial logit model, and multinomial endogenous switching regression (MESR). Results reveal that farm size, access to credit, membership in associations, age, gender, and positive perceptions significantly influenced technology adoption. The MESR analysis shows substantial yield increases with the adoption of the intensification technologies, notably an 80.62% boost when combining all technologies. The study underscores the potential of sustainable intensification to enhance cocoa productivity and resilience to climate variability, offering policy recommendations including improved credit access, enhanced extension services, and supply chain optimization for inputs. This research bridges climate science and agronomic innovation, providing actionable insights for sustaining Nigeria's cocoa economy amidst environmental challenges.

KEYWORDS

cocoa productivity, intensification technologies, MESR, climate change, Nigeria

Introduction

West Africa unequivocally is the major producer of cocoa in the world, with Côte d'Ivoire, Ghana, Nigeria, and Cameroon contributing over 60% of global cocoa production (Shahbandeh, 2021). In 2020, Nigeria was the world's fourth largest producer of Cocoa with 328,263 metric tonnes of cocoa (Worldatlas, 2021) and the third largest exporter (Verter and

Bečvářová, 2014; FAO, 2016). The National Bureau of Statistics Report (2020) asserts that cocoa contributes over 60% by volume to the country's agricultural exports. Due to its favorable soil and climatic conditions, cocoa is cultivated mainly in the southern region of Nigeria. It is the third most exported agricultural commodity in the country, with a total export value of N12 billion in the third quarter of the year 2020. Cocoa has made a significant contribution to the livelihoods of smallholder farmers, serving as a key driver of wealth creation and poverty alleviation (Adegunsoye et al., 2024).

On average, the yield of dried cocoa beans in Nigeria remains at 350–400 kg/ha which is low compared to Malaysia which records 1,700 kg/ha of cocoa, and Ivory Coast which records 800 kg/ha (Aneani et al., 2013). According to statistics on cocoa production in Nigeria, 389,272 tonnes of cocoa was produced annually on average from 2000 to 2010. Between 2015 and 2016 the production fell to 192,000 tonnes annually. Despite increasing to 230,000 tonnes annually since 2017 (ICCO, 2019), the output has yet to reach its utmost potential or even the previous production volume before the year 2000. According to ICCO (2019), the amount of cocoa beans produced in Nigeria during the past years has drastically decreased, falling from 200,000 metric tonnes in 2015–2016 to 245,000 metric tonnes in 2016–2017, then down by 5% in 2017–2018 to 240,000 metric tonnes due to because of declining yields. Six states in Southwest Nigeria—Ondo, Osun, Ekiti, Ogun, Oyo, and Edo produce cocoa, with Ondo and Osun State being classified as major producers and Ogun, Oyo, and Ekiti as medium producers. Afolayan (2020) reported that Osun State produced 74,100 metric tonnes in 2011/2012, while Ondo State is estimated to produce 92,200 metric tonnes annually. Cocoa productivity in Nigeria has been declining in recent years. Studies show that climate change issues are one of the major contributors to low productivity (Suri and Udry, 2022). The declining productivity has also been attributed to other factors, including low adoption of technologies (Fadeyi et al., 2022). The main issues that cocoa industries confront are inconsistency in production, poor access to credit and marketing information, low yield arising from aging trees, the infestation of pests and pathogens, and high cost of inputs and extreme climate events such as droughts, flooding (Hütz-Adams et al., 2016; Kamphuis, 2017; Beckett, 2018). The impact of climate change on cocoa yield is immense since Nigeria largely depends on the local climate for their agricultural production. Increased desert encroachment and severe droughts in the country's north are clear indicators of changing climatic conditions, as are recurring floods and erosion in the south (Kolapo and Kolapo, 2023). Erosion, more frequent flooding, environmental degradation, and thus, a decline in cocoa output have all been connected to climate variability and changes (Echendu, 2020; Kolapo et al., 2022).

In addition, Aneani et al. (2013) asserts that the low level of farmers' adoption of agricultural intensification technology including wrong applications of agricultural innovation are some of the causes of the low yield of cocoa recorded annually in Nigeria. Cocoa farms in Nigeria continue to use natural and simple methods and technologies even though there are a lot of technologies that could improve the yield of cocoa (Bosompem et al., 2011). Many technological innovations have intensified cocoa production but the basic ones are: improved seedlings used for cultivation such as improved seedlings, application of mineral fertilizer and fungicide, and pesticide application.

In addition, the Federal Government of Nigeria began concerted efforts to revive cocoa production in 1999 by setting up a National Cocoa Resuscitation Programme. Its objectives were to improve the cocoa tree stock in the country (through the development of improved varieties and rehabilitation of old trees), increase access to appropriate agrochemicals (pesticides and fungicides), and provide training on good management practices (such as nursery management, rehabilitation techniques, ethical use of agrochemicals, processing of beans among others) for farmers (Wessel and Foluke Quist-Wessel, 2015; Akinnagbe, 2020). Improved cocoa varieties (officially named CRIN TC 1–8) were developed by the Cocoa Research Institute of Nigeria under the Global Cocoa Breeding Initiative project and released in 2010. These varieties are early bearing, high yielding, resistant to major pests and diseases of cocoa, and perhaps most importantly, fertilizer usage and chemicals such as pesticide and fungicide usage are highly adaptable to cocoa ecologies of Nigeria (CRIN, 2016).

Studies have investigated factors related to the adoption of improved farm practices, including the farmer's age, years of education, years of experience, farm location, farm size, availability of credit, sources of information, and number of extension visits (Akinnagbe, 2017; Kolapo et al., 2022; Akinnagbe, 2020; Afolayan, 2020). However, the performance of Nigerian agriculture so far indicates that the farmers have neither used nor accepted most of the technologies being introduced to them (Fawole and Rahji, 2016). Despite several interventions and programs organized by the Nigerian government to tackle the issues confronting cocoa farmers, cocoa bean production has continued to decline (Taiwo, 2016; Afolayan, 2020). In response to the challenges of declining productivity and to boost Nigeria's cocoa industry, there is a need for cocoa farmers to intensify agricultural production to enhance crop productivity.

Several studies have been conducted on the cocoa sectors in Nigeria; price volatility and supply response (Adegunsoye et al., 2024; Wessel and Foluke Quist-Wessel, 2015); technical efficiency (Attipoe, 2020); EU regulations (Raters and Matissek, 2018; Kolapo et al., 2022); adoption of improved technologies (Kumar et al., 2020). However, there is a dearth of information about the determinants and impact of the implementation of intensification technologies on the yield of cocoa, most especially in Ondo State, Nigeria, where larger quantities of cocoa are being produced. Despite the abundance of impact studies in the agricultural literature, empirical investigations on the impact of the adoption of intensification technologies on productivity are still limited, particularly in the West African cocoa industry like Nigeria (Aneani and Ofori-Frimpong, 2013). Against this backdrop, this study sought to analyze the impact of the adoption of intensification technologies on the yield of cocoa in Ondo State, Nigeria.

This research offers a novel contribution by addressing the intersection of climate variability and sustainable agricultural practices in a region critical to Nigeria's cocoa economy, which remains underexplored in the context of localized adaptation strategies. While previous studies have broadly examined climate change impacts on cocoa production in West Africa (Läderach et al., 2013; Schroth et al., 2016), this work uniquely focuses on Southwest Nigeria, a key cocoa-producing zone, where specific climatic shifts, such as unpredictable rainfall patterns and rising temperatures, threaten smallholder livelihoods. Unlike earlier research that often emphasizes regional or national scales (Oyekale, 2017), this study drills down to the sub-regional level, providing granular insights into how local agroecological conditions and farmer practices can be leveraged for sustainable intensification. The novelty lies in its integrated approach, combining climate adaptation with intensification strategies tailored to Southwest Nigeria's socio-economic and environmental context. It explores innovative practices, such as improved planting material, fertilizer, and climate-smart pesticides, that go beyond traditional low-input systems, which have been critiqued for their limited yield potential (Ajayi, 2020). By doing so, it fills a research gap on how to balance productivity gains with environmental sustainability in a climate-stressed region, where cocoa farming has historically driven deforestation and soil degradation (Ruf et al., 2015). Additionally, the study contributes to the literature by assessing the feasibility and effectiveness of these strategies under projected climate scenarios specific to Southwest Nigeria, an area less studied compared to dominant producers like Côte d'Ivoire and Ghana.

The contribution of this research is threefold. First, it provides empirical evidence to inform policymakers and practitioners on scalable, context-specific interventions that enhance cocoa yields without exacerbating ecological harm, aligning with Nigeria's sustainability goals (Ajayi, 2020). Second, it advances the discourse on climate resilience by offering a model for smallholder adaptation that could be adapted to other cocoa-growing regions facing similar challenges. Third, it challenges the prevailing narrative of expansion-driven production by demonstrating how intensification, when sustainably managed, can mitigate the need for further forest encroachment, a critical issue in West Africa's cocoa belt (Schroth et al., 2016). This work thus serves as a timely bridge between climate science, agronomic innovation, and socio-economic realities, offering actionable insights for ensuring the long-term viability of cocoa production in Southwest Nigeria under a changing climate.

Theoretical framework

The theoretical framework for this study is anchored in a synthesis of agricultural innovation adoption theories, climate change adaptation frameworks, and sustainable intensification paradigms. These theories provide a lens to understand how smallholder cocoa farmers in Southwest Nigeria respond to climate variability, adopt intensification technologies, and achieve sustainable productivity gains. The framework integrates three core theoretical perspectives: the Diffusion of Innovations Theory, the Livelihoods Framework, and the Sustainable Intensification (SI) Framework, each contributing to the analysis of technology adoption, climate resilience, and ecological balance in cocoa production.

Diffusion of innovations theory

The Diffusion of Innovations Theory, developed by Everett Rogers, explains how new ideas, practices, or technologies spread within a social system. This theory is central to understanding the adoption of intensification technologies, such as improved seedlings (improved planting materials), fertilizers, and pesticides, among cocoa farmers in Southwest Nigeria. Rogers identifies five stages of adoption (awareness, interest, evaluation, trial, and adoption) and highlights key factors influencing adoption rates, including the innovation's relative advantage, compatibility, complexity, trialability, and observability. In the context of this study, the low adoption of intensification technologies (Aneani et al., 2013; Fadeyi et al., 2022) can be linked to perceived risks, high costs, or incompatibility with traditional farming practices. Socioeconomic characteristics (e.g., age, education, access to credit) and institutional factors (e.g., extension services, associations) further mediate the diffusion process, as evidenced by the study's findings on variables influencing adoption (Kolapo et al., 2022). This theory guides the analysis of why some farmers adopt specific technology packages (e.g., $G_1F_1P_1$) while others remain reliant on basic methods like pesticide use alone ($G_0F_0P_1$).

Sustainable livelihoods framework

The Sustainable Livelihoods Framework (SLF), provides a holistic approach to understanding how farmers leverage assets and strategies to cope with vulnerabilities, such as climate change. The framework emphasizes five capital assets, human, social, natural, physical, and financial, and their interaction with external shocks (e.g., droughts, floods) and institutional structures (e.g., credit access, extension services). In Southwest Nigeria, cocoa farming supports smallholder livelihoods, contributing to wealth creation and poverty reduction (Adegunsoye et al., 2024). However, climate variability threatens these livelihoods through reduced yields and environmental degradation (Echendu, 2020; Kolapo and Kolapo, 2023). The SLF is applied here to explore how access to intensification technologies (physical capital), farmer education and experience (human capital), and cooperative membership (social capital) enable adaptation to climate stressors while enhancing productivity. The study's focus on socioeconomic characteristics (e.g., household size, farm size) and institutional support aligns with SLF's emphasis on asset-based resilience strategies.

Sustainable intensification framework

The Sustainable Intensification (SI) Framework advocates for increasing agricultural productivity per unit of land while minimizing environmental harm and preserving natural resources. SI is particularly relevant in the context of cocoa production in Southwest Nigeria, where low yields (350–400 kg/ha) and climate-induced pressures necessitate innovative practices (Suri and Udry, 2022). The framework emphasizes integrating ecological principles, such as soil fertility management and pest control, with technological advancements to achieve higher outputs sustainably. In this study, intensification technologies (e.g., CRIN TC 1–8 varieties, fertilizers, pesticides) align with SI by boosting yields (e.g., up to 80.62% increase with $G_1F_1P_1$ adoption) without requiring further land expansion, thus mitigating deforestation risks (Ruf et al., 2015). The SI Framework also underscores the importance of balancing productivity with climate resilience, a critical consideration given Nigeria's changing climatic conditions (Kolapo et al., 2022). This theory frames the study's investigation into how intensification can be both productive and sustainable under local agroecological constraints.

The integration of these theories forms a robust theoretical foundation for the research. The Diffusion of Innovations Theory explains the process and determinants of adopting intensification technologies, addressing "why" and "how" farmers choose specific practices. The Sustainable Livelihoods Framework contextualizes these choices within the broader socio-economic and environmental vulnerabilities faced by cocoa farmers, emphasizing resilience to climate change. The Sustainable Intensification Framework ties these elements together by focusing on the outcome, enhanced productivity with minimal ecological cost, under a changing climate. Together, they provide a multidimensional lens to analyze the interplay between technology adoption, livelihood security, and sustainable cocoa production in Southwest Nigeria. This framework is operationalized through the study's methodology and objectives. The multinomial logit model tests the influence of socioeconomic and institutional factors (e.g., farm size, credit access, perception) on adoption decisions, aligning with Diffusion of Innovations. The MESR analysis quantifies the productivity impacts of intensification technologies, reflecting SI's focus on yield gains and sustainability. Meanwhile, the emphasis on climate variability (e.g., erratic rainfall, rising temperatures) and farmer adaptation strategies ties into the SLF's vulnerability context. By situating Ondo State within Nigeria's cocoa economy, the framework addresses the research's novelty: exploring localized, climate-smart intensification strategies in a critical yet understudied region (Läderach et al., 2013; Schroth et al., 2016).

Methodology

Study area

The study was conducted in Ondo State, Nigeria. The State is located in the south-western zone of Nigeria between latitude 7°10′North and longitude 5°05′East of the Greenwich Meridian. The climate area is highly favorable for the agrarian activities of her teeming population of 3,423, 535 people [National Population Commission (NPC), 2007]. The tropical climate of the state is mainly of two seasons: rainy season (April–October) and dry season (November–March) with temperature ranges between 21 °C to 29 °C, an annual rainfall of between 2,000 mm to 1,200 mm per annum, and humidity is relatively high. The state is divided into 18 Local Government Areas (LGAs). It is bounded in the North by Kogi and Ekiti States; Edo and Delta States in the East; Ogun and Osun States in the West and Atlantic Ocean in the South. Six states in Southwest Nigeria-Ondo, Osun, Ekiti, Ogun, Oyo, and Edo produce cocoa, with Ondo and Osun being classified as major producers and Ogun, Oyo, and Ekiti as medium producers. Osun State produced 74,100 metric tonnes in 2011/2012, compared to Ondo State's estimated output capacity of 92,200 metric tonnes annually (Afolayan, 2020). Figure 1 shows the map of the study area, the Southwest of Nigeria, Ondo state as well as the LGAs. Aside from cocoa production, farmers also cultivate other cash crops (such as oil palm, kola and rubber) and food crops (such as maize, cassava and yam) which are common in Southwest Nigeria (Falola and Fakayode, 2014). About 60% of the nation's cocoa output is produced in Ondo State (IITA, 2007). Farming in the State is characterized by small farm sizes, inadequate supply of modern farming inputs, poor state of rural infrastructure, aging farmers and cocoa trees, significant post-harvest losses, dependence on rain for farming, and lack of interest among youths in agricultural activities.

Sampling technique and sample size

A multi-stage sampling technique was used in selecting cocoa producers in the study area. The first stage involved a purposive selection of two (2) cocoa-producing Local Government Areas (LGAs) in the State due to the high concentration of cocoa producers in the LGAs. In the second stage, four (4) villages were randomly selected from each of the LGAs. In the third stage, fifteen (15) farmers were randomly selected from each sampled village to give a total of 120 respondents, that was used for the study. A structured questionnaire was used to collect primary data from cocoa farmers using a multi-stage sampling technique. The data collected includes the socioeconomic characteristics of the respondents such as age, marital status, education level, household size, farming experience; access to the intensification technologies and the intensity of the adoption of the new technology, differences in productivity among the respondents who have access to and do not have access to the intensification technologies.

Method of data analysis

The data collected for the study were analyzed using descriptive analysis, Multinomial logit model and Multinomial endogenous switching regression. Descriptive statistics such as frequencies, percentages were used to examine the socio-economic characteristics (such as age, sex, farming experience, household size, educational status, access to credit) and levels of adoption among the respondents. They were also used to identify the intensification technologies adopted and the effect of the adoption.

Multinomial logit model

The multinomial logit (MNL) regression is an analytical method employed to assess the choice of alternative combinations of techniques in smallholder farming systems (Babulo et al., 2008). This approach involves studying the selection of various technologies among a choice set involving of all likely combinations. The marginal effects of farmers' and farms' characteristics on choice probabilities are appraised built upon estimates from an MNL choice model.

Consider a rational farmer i with the primary objective of maximizing productivity, p_i by comparing the benefits he enjoys from adopting m alternative options. A rational farmer will choose package k ($G_1F_0P_1$, $G_0F_1P_1$, $G_1F_1P_1$) (Table 1), over any alternative package m($G_0F_0P_1$) if the net benefit is positive. Thus, $\Delta p_{im} = p_{ik} - p_{im} > 0 \; m \neq k$. The index function to model the adoption of the package can be specified in Equation 1:

$$\lambda_k = \sum_{m \neq k}^{k} p_k \left[\frac{\hat{P}_{im} 1n(\hat{P}_{im})}{1 - \hat{P}_{im}} + In\left(\hat{P}_{ik}\right) \right] \tag{1}$$

where p^*_{ik} is a latent variable defining the expected net benefits a farmer derives from adopting package k, Z_i represents observed covariates (socioeconomic, farm-specific, among others) ϕ_k and δ_{ik} are the unknown parameter and an error term accounting for unobserved characteristics, respectively. If J is the index of farmers' choice of the intensification technologies package, then:

$$J = \begin{cases} 1 \, if \; p^*_{i1} > 0 \max\left(p_{im}\right) or \; \eta_{i1} < 0 \\ \quad for \; all \; m \neq k \\ K \, if \; p^*_{ik} > 0 \max\left(p_{im}\right) or \; \eta_{ik} < 0 \end{cases} \tag{2}$$

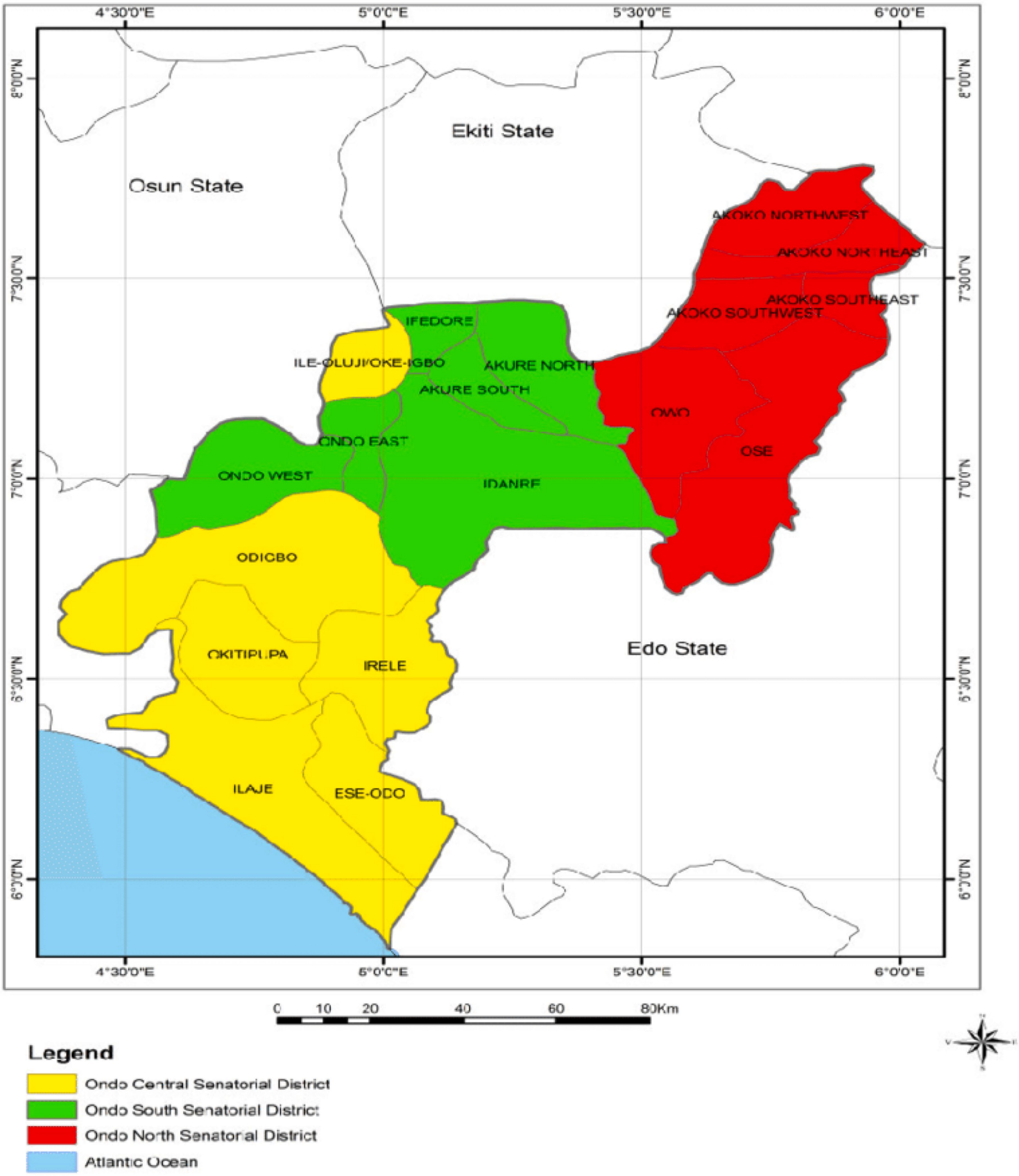

FIGURE 1
Map of Ondo state showing the LGAs. Source: Owolabi and Okunlola (2015).

The index function in Equation 2 means that a cocoa farmer will use any package k if and only if k gives him/her the greatest expected benefit than any other package. Thus, if in Equation 3:

$$p_{ik} = \max\left(p^*{}_{ik} - p^*{}_{im}\right) > 0, m \neq k \tag{3}$$

If the error term (δ_{ik}) has an identical and Gumbel distribution, then the probability that an ith cocoa farmer will select package k can be expressed by a multinomial logit model according to McFadden (1973) in Equation 4:

TABLE 1 Specification of different combinations of ITs.

Packages combinations	G_1	G_0	F_1	F_0	P_1	P_0	Freq	%
G_0 F_0 P_1		✓		✓	✓		86	71.67
G_1 F_0 P_1	✓			✓	✓		14	11.67
G_0 F_1 P_1		✓	✓		✓		7	5.83
G_1 F_1 P_1	✓		✓		✓		13	10.83
Total							120	100

G_1, use improved planting; G_0, do not use improved planting; F_1, use fertilizer; F_0, do not use fertilizer; P_1, use pesticide.

$$prob = \Pr\left(p_{ik} < 0 / Z_i\right) = \frac{\exp\left(Z_i \beta_k\right)}{\sum_{m=1}^{k} \exp\left(Z_i \beta_m\right)} \quad (4)$$

The empirical model can be specified in Equation 5:

$$Y_i = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_8 X_8 + \varepsilon \quad (5)$$

Where,

Y_i, dependent variable (intensification technologies such as ($G_1F_0P_1$, $G_0F_1P_1$, $G_1F_1P_1$),

$G_1F_0P_1$, farmers that combined pesticides with improved planting material,

$G_0F_1P_1$, farmers that combined pesticides with fertilizers, and

$G_1F_1P_1$, farmers that combined pesticides with fertilizer and improved planting material.

The base reference are the farmers that use only pesticide application ($G_0F_0P_1$). $X_1 - X_{10}$ = vector of independent variables (individual and household characteristics, household assets variable and institutional variables) that might influence the adoption decision, β_0 = constant term $\beta_1 - \beta_{10}$ = coefficients of independent variables estimated and ε = error terms.

The definition of explanatory variables is: X_1 = Age of cocoa farmer (years); X_2 = Farm Experience (years); X_3 = Household size (number); X_4 = Farm size (hectares); X_5 = Extension visits (extension visit = 1, no = 0); X_6 = Access to credit (access = 1, no = 0); X_7 = Belong to Association (yes = 1, no = 0); X_8 = Access to Information (access = 1, no = 0); X_9 = Gender (male = 1, otherwise = 0); X_{10} = Perception (categorical).

Multinomial endogenous switching regression

The MESR model involves estimating an Ordinary Least Squares (OLS) regression with selectivity correction to study the association between the productivity of cocoa and a set of covariates for specific technology choice, i.e., ($G_0F_0P_1$), k = 1 (non-adoption as a base category), $G_1F_0P_1$, k = 2, $G_0F_1P_1$ k = 3 and $G_1F_1P_1$ = 4.

The productivity equation for each possible regime is specified in Equation 6:

$$\begin{cases} regime1: Y_{i1} = \beta_1 X_i + \varepsilon_{i1} \; if \; j = 1 \\ \qquad\qquad k = 2,3,4 \\ regimek: Y_{ik} = \beta_k X_i + \varepsilon_{i1} \; if \; j = k \end{cases} \quad (6)$$

where X_is are vectors of exogenous covariates, β's are vectors of parameters; and ε_{i1} and ε_{iK} are random disturbance terms. The error terms have distributions $E(\varepsilon_{ik}/Z, X) = 0$ and variance $(\varepsilon_{ik}/Z, X) = \sigma_k^2$. Y_{ik}s are the productivity indicators for an ith cocoa farmer in regime k. In this case, Y_{ik} is observed if and only if package k is adopted, where $\Pi_{ik}{}^* > \max_{m \neq k} (\Pi_{im}{}^*)$. The OLS models in Equation 1 are likely to produce biased estimates if the two error terms (ε and δ) in Equations 1, 4 are correlated.

The linearity assumption of the DM model can be specified in Equation 7:

$$E\left(\delta_{ik} / \varepsilon_{i1 \ldots} \varepsilon_{ik}\right) = \sigma_k \sum_{m=1}^{k} r_k \left(\varepsilon_{im} - E\left(\varepsilon_{im}\right)\right) \quad (7)$$

By construction, the correlation between the two error terms δ and ε add up to zero. Thus, if this assumption is valid, then the multinomial endogenous switching regression can be expressed in Equation 8:

$$\begin{cases} regime1: Y_{i1} = \beta_1 X_i + \sigma_1 \lambda_1 + \phi_{i1} \; if \; j = 1 \\ regimek: Y_{ik} = \beta_k X_i + \sigma_k \lambda_k + \phi_{ki} \; if \; j = k \end{cases} \quad (8)$$

Where σ_j denotes covariance between the error terms δ of Equation 1 and ε of Equation 4; λ_k is the inverse Mills ratio calculated from the multinomial logit model in Equation 2. The inverse Mills ratio (λ_k) ni is given in Equation 9:

$$\lambda_k = \sum_{m \neq k}^{k} p_k \left[\frac{\hat{P}_{im} \, 1n(\hat{P}_{im})}{1 - \hat{P}_{im}} + In\left(\hat{P}_{ik}\right) \right] \quad (9)$$

where p_k defines the correlation coefficient of the three error terms, δ,ε and ϕ. The error terms have expected zero values. There is a possibility of heteroskedasticity in generating the regressor (λ_k) for the inverse Mills ratio. This was accounted for by the use of bootstrap standard errors. We used access to credit as an instrumental variable. This variable is significant in the adoption of pesticide and improved planting material (G1F0P1) at the 5% level. It serves as an IV because it influences adoption but is assumed to affect yield only through adoption, not directly. Credit access often determines the ability to purchase inputs like improved seedlings or pesticides, making it a plausible instrument.

Conditional expectations, treatment, and heterogeneity effects

The multinomial endogenous switching regression (MESR) was employed to compute the average treatment effect (ATT) on the treated by comparing the predicted values of the outcome of the treated (adopters) and untreated (non-adopters) in actual and counterfactual situations. The ATT is defined as the change in the outcome variable of interest attributed to $G_1F_0P_1$, $G_0F_1P_1$ and $G_1F_1P_1$, adoption only. Following Khonje et al. (2015), the restrictive expectations for the welfare variables in both the actual and their counterfactual set-ups is specified as:

Adopters with adoption (actual),

$$E\left(Y_{ik} | j = \mathrm{k}\right) = \beta_k X_{ki} + \sigma_k \lambda_k \quad (10)$$

Adopters had they decided not to adopt (counterfactuals),

$$E\left(Y_{i1} | j = \mathrm{k}\right) = \beta_1 X_{ki} + \sigma_1 \lambda_k \quad (11)$$

Equation 10 represents the real expectations observed in the sample. Equation 11 represents the counterfactual expected outcome. In this case, the average treatment effect on the treated (ATT) is calculated as the difference between Equations 10, 11. This is expressed in Equation 12 as:

$$ATT = E\left(Y_{ik} \middle| j = \text{k}\right) - E\left(Y_{i1} \middle| j = \text{k}\right) = X_{1i}\left(\beta_k - \beta_1\right) + \lambda_2\left(\sigma_k - \sigma_1\right) \quad (12)$$

From Equation 12, the first terms on the right-hand side capture the expected average outcome of adopters if they had similar characteristics to non-adopters. The potential effects of the differences in unobserved variables are obtained by the second term (λ) which is the selection term.

Results and discussion

Descriptive analysis of the socioeconomic characteristics of the respondents

This section presents the description of socioeconomic characteristics to provide background information of the respondents in the study area. The socio-economic characteristics such as age, marital status, gender, year of education, farming experience, and household size, were described.

Table 2 shows the average age of cocoa farmers was 52.2 ± 13.615 years. The majority of the farmers (47.50%) fall within the age bracket of 46 years and 65 years. The findings revealed that the majority of the cocoa farmers involved in cocoa production are old, which could affect the use of intensification technologies in cocoa production. Also, the age of farmers determines the number of useful man-days of labor available (or the managerial skill). This finding supports the findings of Kolapo et al. (2022), who found that the average age of a cocoa farmer in Nigeria is 50 years.

The result in Table 2 shows that male farmers make up 95.0 percent of the sampled farmers. In the study area, cocoa cultivation is a male-dominated activity; this could be because women work in processing. The male predominance in cocoa cultivation can be ascribed to the significant demands of time and effort required in such an enterprise. It's also possible that the cultural context recognizes male children as the only ones entitled to inheritance because males have easy access to land, especially as the majority of them are the heads of their numerous houses. This confirms the findings of Lawal et al. (2016), who found cocoa production to be a male-dominated sector. According to Table 2, the majority of respondents (95.83%) were married, with only 2.50% single and 1.67% widowed. This suggests that cocoa farmers have significant obligations that may require their dedication to their chosen work to ensure a steady flow of revenue to meet the demands of the family, which may influence their decision toward the adoption of intensification technologies. This complies with Sowunmi et al. (2019), who revealed that the majority of cocoa farmers were married. The result presented in Table 2 shows that the majority of respondents (80%) had a formal education, while 20% of farmers had no formal education. About 34.17% attended primary school, 40.83% had secondary education, just only 5% attended tertiary institutions. This is an indication that literate farmers were involved in cocoa production in the study area. The result supported the findings of Lawal et al. (2016) and Kolapo et al. (2022) who reported that average cocoa farmers were literate. This means that they can understand and apply new technology, such

TABLE 2 Socioeconomic characteristics of the respondents (*N* = 120).

Variable (category)	Frequency	Percentage
Age		
26–45	43	35.83
46–65	57	47.50
>65	20	16.67
Total	120	100
Mean ± std	52.2 ± 13.615	
Gender		
Male	114	95.00
Female	6	5.00
Marital status		
Single	3	2.50
Married	115	95.83
Widowed	2	1.67
Education		
No formal education	24	20.00
Primary education	41	34.17
Secondary education	49	40.83
Tertiary education	6	5.00
Household size		
≤5	19	15.83
6–10	75	62.50
11–15	21	17.50
≥16	5	4.17
Mean ± std	8.41 ± 3.955	
Access to credit		
No access	95	79.17
Access	25	20.83
Size of cocoa farm (ha)		
<2 ha	13	10.83
2–4	82	68.33
>4	25	20.83
Mean ± std	3.075 ± 1.238	
Experience (years)		
<5	6	5.00
5–10	15	12.50
11–15	15	12.50
>15	84	70.00
Mean ± std	26.675 ± 15.392	
Extension visit		
No	94	78.33
Yes	26	21.67
Membership status		
Yes	42	35.00
No	78	65.00

Source: Author's computation.

as the use of fertilizer and pesticides that can boost their productivity, profitability, and efficiency. Tijani and Sofoluwe (2012) assert that farmers with greater educational standing are better competent to evaluate technology. A knowledgeable farmer can read magazines, bulletins, and even the pesticide and fertilizer label instructions. The number of individuals who live together, eat at the same table, and manage the household's finances collectively is referred to as the household size. The average household size is 8.41 ± 3.955 (Table 2). This is consistent with the findings of Lawal et al. (2016), who found that the majority of farmers have households with more than six people. The majority of respondents (62.50%) who had a household of at least six persons show that there is family labor available in the research area for the cultivation of cocoa. This could mean that farmers in the research area employ family members to reduce labor expenses and raise profits. This conclusion is in line with that of Sowunmi et al. (2019), who found that farmers with large household sizes use family labor when there is a shortage of agricultural labor. Therefore, there is a decrease in the cost of labor. The breaking of pods, fermentation, drying, and weighing of the cocoa beans are claimed to have been helped by these family members during the height of farming activity. Access to credit increases farmer's yield and helps improve the standard of living for cocoa farmers through the acquisition of necessary inputs. Table 2 reveals that 79.17 percent of people lacked access to credit, this might be because the great majority of them lacked collateral and access to credit-related information. This implies that due to a shortage of funding, cocoa farmers could not be able to purchase the necessary pesticides and other inputs. It might also interfere with their intentions to expand their farm. Obuobisa-Darko (2015) asserts that access to credit has an impact on farmers' decisions on the adoption of technologies. The result presented in Table 2 shows that 10.84 percent of cocoa farmers have farms with less than 2 hectares of land, while 68.33 percent have farms between 2.1 and 4 hectares. The average size of the farm was 3.075 ± 1.238 hectares, this revealed that the majority of cocoa farmers operate at a small-scale level conforming to the study of Oluyole and Taiwo (2016). Farming experience is a process through which farmers perceive and participate, accumulate knowledge, and adopt technologies, since cocoa cultivation is labor-intensive, there are many unpredictability in its output, including infestations of pests and diseases, weather, and other factors. However, the impact can be reduced by using experience. Table 2 shows that the average size of farmers' experience is 26.675 (±15.392) years. This is a clear indicator that cocoa farmers have the necessary experience to be able to adapt to new technology. This is similar to the findings of Awoyemi and Aderinoye-Abdulwahab (2019), who found that the majority of cocoa farmers are experienced. From Table 2, about 21.67% of farmers had access to extension services, and 78.33% of farmers had never been visited by an extension agent. Since extension visits are crucial for keeping farmers up to date on new agricultural technology, this implies that majority of new techniques and information regarding the use of improved planting materials, fertilizer and pesticides may not be adequately distributed to farmers. Popoola et al. (2015) reported that 78 percent of cocoa farmers lacked access to extension services, and their findings are in accordance with our results. Farmers that join an association, such as Cocoa Farmers Association of Nigeria (CFAN) and Cocoa Association of Nigeria (CAN) have access to information on modern production techniques, purchasing inputs in bulk as well as exchanging labor (Onubuogu et al., 2014). The proportion of farmers who are members of an association is displayed in Table 2. It shows that 35% of cocoa farmers belong to one or more cooperative societies, compared to 65% of farmers who do not belong to any cooperative organization. The majority of farmers lack access to finance since they do not belong to any associations, which will prevent them from increasing their output and enhancing their productivity.

Perception and source of information about intensification technologies

Farmers may perceive adopting new technologies as a risk due to uncertainties associated with their performance and market demand. They may be resistant to change and view intensification technologies as a departure from their traditional methods and also the cost associated with these technologies may deter farmers from adopting these technologies. Table 3 shows that 79.17% slightly agreed with the adoption of intensification technologies to boost their productivity while 20.83% completely agreed. As presented in Table 3, the informal source of information about intensification technologies represents 55% of people who rely on informal sources (friends, family/relatives, community, word-of-mouth, radio) which indicates a higher preference for information about technology adoption. It suggests that social influence and peer-to-peer communication play a crucial role in disseminating cocoa information. The formal source of information represents 45% of people who rely on formal sources (publications, academic journals, research institutes, extension agents, ministry of agriculture) which shows that formal sources are yet to be fully operative among the cocoa farmers in the study area. This finding agrees with Adeogun et al. (2010) who found informal sources as the most sought means of information by cocoa farmers in Nigeria. These informal sources are often unreliable. Adebiyi and Okunlola (2013) found that inadequate information is one of the major impediments affecting the adoption of cocoa-improved technology among farmers in Ondo State.

Types of intensification technologies adopted by the farmers

The types of intensification technology adopted by cocoa farmers are presented in Figure 2. Three types of intensification technologies were identified in the study area namely: Improved planting materials, fertilizers, and pesticides. The respondents were classified into Adopters (farmers who used any of the intensification technologies) and non-adopters (farmers who did not use any intensification technologies). The former includes adopters of improved planting materials; adopters of fertilizer; and adopters of pesticides. As revealed in Figure 2 all of the farmers adopted the use of pesticides; 16.67% adopted fertilizer and 23.33% adopted GPM. Farmers could be interested in the intensification technologies package but may not adopt the whole items in the package due to some institutional factors. The latter includes farmers that did not adopt any of the intensification technologies introduced to the area, 83.33% did not adopt fertilizer and 76.67% did not adopt GPM and could be attributed to ineffective extension service, high cost-effectiveness of the technology. On the other hand, there are four categories of adopters in the study area as shown in Figure 3 and the various combination is shown in Table 1.

TABLE 3 Distribution of respondents by perception (slightly agree or completely agree) and source of information of intensification technologies.

Items	Frequency	Percentage
Perception		
Slightly agree	95	79.17
Completely agree	25	20.83
Source of information		
Informal	66	55.00
Formal	54	45.00

Source: Author's computation.

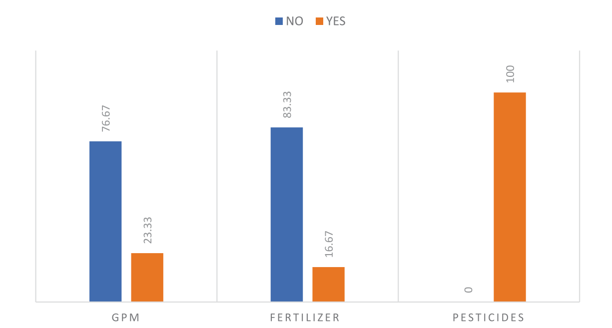

FIGURE 2
Types of intensification technologies adopted by the farmers.

The first categories are the adopters of pesticides only (71.67%), the second category are the adopters of combined pesticide and GPM (11.67%), the third categories are the adopters of pesticide and fertilizers (5.83%), and lastly the adopters of all combinations of the ITs (pesticides, GPM, and fertilizers) with 10.83%. This shows that intensification technologies introduced to cocoa farmers have been partially adopted.

Factors influencing the adoption of intensification technologies

The regression results of the multinomial logit model, which examines the factors influencing the adoption of intensification technologies among farmers, are presented in Table 4. The category of individuals who did not adopt intensification technologies ($G_0F_0P_{1)}$ served as the reference group in the multinomial logit model. The null hypothesis that all regression coefficients are jointly equal to zero was rejected based on the Wald test (χ^2). The Wald statistic for the regression model demonstrated statistical significance at a significance level of 1%, indicating a significant level of goodness-of-fit. The coefficients serve as indicators of the extent to which a particular variable influences the probability of utilizing intensification technologies. The model appears to explain a significant portion of the variability in the outcome variable, according to the pseudo R^2 value of 0.5121. The coefficients for the other three groups (pesticide and improved planting material, pesticide and fertilizer, and all intensification technologies) are compared to the base outcome of the regression of those that use only pesticide application.

Pesticide and improved planting material

In the first model of the multinomial logit regression, three variables were found to be significantly influencing the use of pesticides (PT) and improved planting materials (GPM). Farm size was positively and significantly influenced the use of pesticides (PT) and improved planting materials at 10%. It was expected to influence the adoption of PT & GPM positively because farm size indicates the intensity of crop cultivation. The larger the size of the farm the more cost it incurred to run it which denotes higher investments; hence they will need to adopt technology that will increase their yield and income. This result corroborates the results of Corbeels et al. (2016) that optimum farm size is required for the use of intensification technologies.

The variable membership of association was positively significant at 10%. This implies that being a member of an association will tend to lead to using the techniques. In accordance to the expected result, the association provides their members with needed information which helps increase their farm yield and also gives them access to some farm resources. Thus, being a member of an association affords the farmers up-to-date information regarding the various combination of intensification technologies that can help them improve cocoa productivity.

The credit variable was positive and significant at 5%, suggesting that access to credit increases the likelihood of employing this technique. According to the credit variable's significant coefficient, farmers with credit access are more likely to utilize pesticides and improved planting materials. The fact that farmers with access to credit have more financial resources, allowing them to buy these supplies, might be responsible for this outcome.

Pesticide and fertilizer

Age has a positive and significant relationship with pesticide and fertilizer use at 1%, suggesting that older farmers are more likely to use these techniques. This could be because older farmers often have more experience in farming and are more likely to be aware of the advantages of applying pesticides and fertilizer. Additionally, older farmers may have more good relationships with input distributors and extension workers, which can improve their access to resources and information about the usage of pesticides and fertilizers. This result agrees with the result of Choudhary et al. (2018) that older farmers are more likely to adopt conservation agricultural farming systems. The variables of farm size and association exhibited statistically significant positive and negative relationships at the 10 and 5% significance levels, respectively.

The findings indicate a statistically significant and positive correlation between yield (cocoa output) and the utilization of pesticides and fertilizers at a significance level of 1%. This suggests that the appropriate application of pesticides and fertilizers by farmers can result in enhanced crop yields. Pesticides have the capacity to efficiently manage pests, diseases, and weeds, thereby mitigating potential harm or diminished crop productivity. By implementing measures to safeguard crops against these potential hazards, farmers can attain elevated yields and consequently augment their overall productivity. Additionally, the prudent use of fertilizers may increase soil fertility and furnish vital nutrients to cultivated crops.

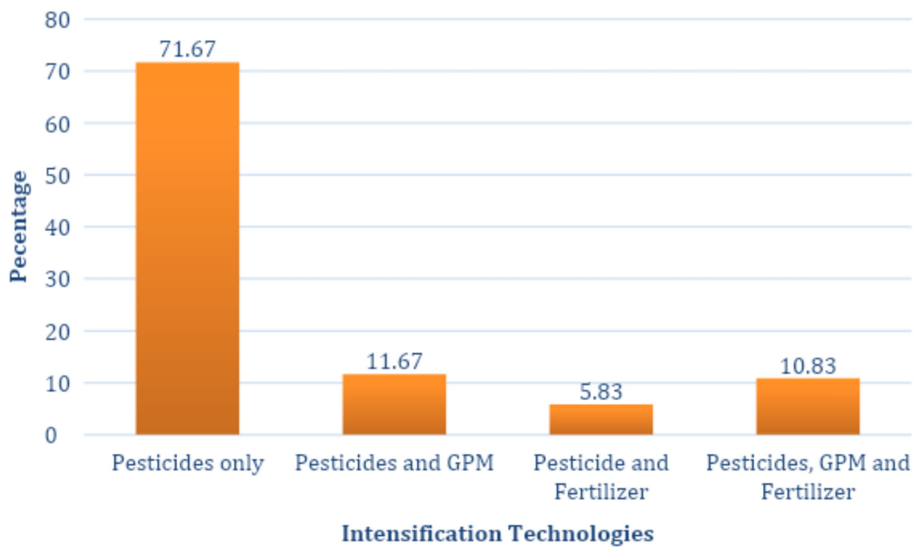

FIGURE 3
Combination of intensification technologies adopted by the farmers.

TABLE 4 Parameter estimates of the multinomial regression model.

Variables	$(G_1F_0P_1)$			$(G_0F_1P_1)$			$(G_1F_1P_1)$		
	Coef.	Std. Err.	t-value	Coef.	Std. Err.	t-value	Coef.	Std. Err.	t-value
Age	0.039	0.045	0.86	0.289***	0.107	2.71	0.039	0.035	1.12
Household size	−0.215	0.147	−1.46	0.016	0.206	0.08	−0.043	0.122	−0.35
Farm size	1.289*	0.675	1.91	1.439*	0.850	1.69	1.007*	0.533	1.89
Education level	1.767	1.39	0.112	0.017	0.013	1.27	0.015	0.032	0.47
Information source	−1.383	1.082	−1.28	1.262	1.544	0.82	−1.998**	0.968	−2.06
Extension services	0.677	1.298	0.52	2.741	3.051	0.90	0.188	1.039	0.18
Membership of association	2.146*	1.15	1.87	−8.086**	3.597	−2.25	−1.057	0.943	−1.12
Farming experience	−0.055	0.041	−1.34	0.003	0.042	0.07	−0.015	0.032	−0.47
Gender	0.017	0.013	1.27	0.033*	0.020	1.65	0.026**	0.012	2.20
Perception	22.373	1.95e3	0.01	7.464***	2.458	3.04	3.880***	1.045	3.71
Credit	2.558**	1.239	2.07	2.457	1.767	1.39	0.112	0.964	0.12
Constant	−24.887	1950.262	−0.01	−31.176***	10.221	−3.05	−9.049	3.479	−2.60
Wald test χ^2 (30)	110.105								
P	0.000								

$G_0F_0P_1$ is the based category. Significance levels: *: 10%; **: 5%; ***: 1%. Absolute value of z statistics in parenthesis.

Consequently, this phenomenon results in enhanced plant health, improved growth rates, and ultimately increased productivity. Additionally, the perception variable has a positive significant relationship with pesticide and fertilizer use at 1%, indicating that farmers who have a positive perception about the techniques are more inclined to utilize this technology. Their adoption of these technologies can be sparked by this awareness in order to increase their yields and profitability.

Pesticide, improved planting material, and fertilizer

The study revealed that variables such as farm size, gender, and perception have a statistically significant and positive impact on the adoption of various technological combinations. This finding aligns with the earlier model that was discussed. This implies that cocoa farmers with larger farm sizes are more likely to combine the various intensification technologies for sustainable cocoa production while increasing their yield. In addition, male cocoa farmers are more likely to implement a combination of the three identified intensification technologies for cocoa improved cocoa yield. This might be attributed to the disparities usually observed in access to resources, farm inputs, and up-to-date information among the two genders. The female gender has been observed to have unequal access to resources and farming inputs and technologies when compared with their male counterparts. Farmers with positive perceptions about the usefulness of intensification technologies are more likely to combine these three intensification technologies to improve their cocoa yield.

Lastly, the information source variable had a negative significant association with the use of all the technologies, this could be a result of a lack of accurate or accessible information which can hinder the adoption of intensification technologies and could be linked to factors such as inadequate extension services, limited access to knowledge sources, or communication gaps between technology providers and potential adopters.

Average treatment effects of intensification technologies

We estimated the conditional average effects of the adoption of intensification technologies on cocoa productivity. ATT measures the effect of the outcome variables of farmers who adopt ITs as compared with the outcome variables of the same farmers if they had not adopted ITs. This was calculated using Equation 12. While ATU estimates the outcome of farmers who did not adopt ITs compared to the same farmers if they had adopted. It was estimated by the use of Equation 12. The MESR average treatment effects (ATT) of the alternative package of intensification technologies adoption and implementation were presented in Table 5. Rosenbaum (2002) ascertained that the measure of treatment effect is a better approach to estimating the usefulness of technology among farmers.

The results in Table 5, shows the use of ITs significantly increases the yields of adopters and also has the potential to increase that of the non-adopters of ITs. Specifically, the causal effect of using both pesticides and GPM ($G_1F_0P_1$) brought about a 183.38 increase in cocoa yields, representing about a 46.33% increase in cocoa yields of the adopters. The causal effect of using both pesticides and fertilizers ($G_0F_1P_1$) brought about a 16.87 increase in cocoa yields, representing about a 7.28% increase in cocoa yields of the adopters. The highest yield was recorded by those that used all combinations ($G_1F_1P_1$) with an 883.53 increase in cocoa yield, representing about an 80.62% increase in cocoa yields of the adopters. These findings are in line with the studies of Bidzakin et al. (2019), who show that adoption of improved technology has the potential to improve farm yields.

TABLE 5 Average treatment effects (ATT) of intensification technologies.

Outcome variable	Treatment effect	Std err.	*p* value	% increase
$G_1F_0P_1$	183.378***	59.775	0.002	46.33
$G_0F_1P_1$	16.880	67.211	0.803	7.28
$G_1F_1P_1$	883.539***	215.145	0.000	80.62
POmean				
$G_0F_0P_0$	212.402***	10.793	0.000	

Significance levels: *** = 1%.

Robustness check (propensity score matching)

Table 6 presents the results of a Propensity Score Matching (PSM) analysis. PSM is an econometric technique used to estimate the causal effects of a treatment (in this case, the adoption of sustainable intensification technologies) by matching treated units (farmers who adopted the technologies) with control units (non-adopters) based on observable characteristics. The table reports results using two matching methods—Nearest Neighbor Matching (NNM) and Kernel-Based Matching—focusing on cocoa yield (measured in kilograms) as the outcome variable. PSM aims to reduce selection bias in observational data by balancing the distribution of covariates between treated and control groups. In this study, the treatment is the adoption of sustainable intensification technologies (e.g., improved seedlings, fertilizers, and pesticides), and the goal is to estimate their impact on cocoa yield in Southwest Nigeria.

Both NNM and Kernel-Based Matching confirm that sustainable intensification technologies significantly increase cocoa yields. The ATT estimates (40.101 kg for NNM, 37.070 kg for Kernel) align with the broader study's MESR results (Table 5), where adoption of combined technologies (e.g., G1F1P1) yielded an 80.62% increase (~883.539 kg). The smaller PSM estimates suggest a more conservative impact, possibly due to different technology combinations or sample adjustments. The NNM and Kernel methods yield similar results, with NNM showing a slightly larger ATT (40.101 kg vs. 37.070 kg). This robustness enhances confidence in the findings, as Kernel matching uses more control units, potentially reducing bias but increasing variance (Caliendo and Kopeinig, 2008). The ATT exceeds the ATU (e.g., 40.101 kg vs. 12.087 kg in NNM), indicating that current adopters benefit more than non-adopters would. This could reflect adopters' better access to resources (e.g., credit, extension services) or experience, as noted in the study's MNL results (Table 4). The PSM results in Table 6 demonstrate that sustainable intensification technologies significantly increase cocoa yields.

Environmental implications of sustainable cocoa intensification

While the primary focus of this study is on enhancing cocoa yields through the adoption of intensification technologies, the environmental implications of such practices are equally critical, particularly in the context of sustainable agricultural development. The use of improved planting materials, fertilizers, and pesticides, if not carefully managed, poses risks to soil health, biodiversity, and water quality. However, when implemented under a sustainable intensification framework, these technologies can support environmental goals by reducing the need for land expansion and thus mitigating deforestation, a historical consequence of cocoa farming in West Africa (Ruf et al., 2015). The adoption of CRIN TC 1–8 varieties, which are pest-resistant and climate-resilient, offers an opportunity to enhance productivity without proportionately increasing chemical inputs, thereby minimizing ecological harm (CRIN, 2016; Kolapo et al., 2022). Moreover, the study's findings that adoption of all

TABLE 6 Effects of sustainable intensification technologies on cocoa yield.

Variables	Sample	Treated	Controls	Differences	Std. err	t-statistics
Nearest neighbor matching (NNM)						
Yield (kg)	Unmatched	486.632	309.649	56.983	11.092	4.24
	ATT	496.632	296.531	30.101***	12.215	3.28
	ATU	549.649	294.736	14.087	-	-
	ATE			19.452	-	-
	Effect (%)			0.57***		
Kernel-Based Matching						
Yield (kg)	Unmatched	493.632	312.649	27.649	11.092	4.24
	ATT	402.632	234.562	29.070***	13.422	2.76
	ATU	185.649	103.184	10.535	-	-
	ATE			17.758		
	Effect (%)			0.44***		

***Significance at 1% level of probability.

three intensification technologies (G1F1P1) yields an 80.62% productivity gain underscore the potential for maximizing output per unit area, aligning with the core tenets of environmental sustainability (Schroth et al., 2016). Nonetheless, limited access to extension services and reliance on informal information channels (Adeogun et al., 2010) may compromise the proper use of agrochemicals, exacerbating environmental risks such as runoff and pollution. Therefore, integrated support systems, including training, monitoring, and environmentally sound input management, are essential to ensure that productivity gains do not come at the expense of ecosystem integrity. A balanced approach that promotes agroecological practices alongside technological innovation is vital to achieving both yield improvements and long-term environmental stewardship.

Conclusion and recommendations

This study contributed to existing knowledge by highlighting factors determining farmers' decisions to use and adopt intensification technologies and also provided information on the effect of intensification technologies on productivity. The adoption of intensification technologies has been shown to have a significant contribution to the productivity of cocoa in Ondo State. Results from the multinomial logit model (MNL) showed that different household socioeconomic characteristics, institutional, and input variables influence the likelihood of farmers adopting the intensification technologies. Age of farmers, farm size, credit, information, perception, and gender have all been identified as drivers of the adoption of intensification technologies. The result from MESR showed that the use of intensification technologies significantly increases the yields of adopters and also had the potential to increase that of the non-adopters of intensification technologies. To sustain, improve cocoa quality and also increase the productivity of cocoa in Nigeria the following policy recommendations are drawn from the study; the study recommends the improvement of institutional capacities, especially in the areas of credit accessibility and collaboration with financial institutions to promote technology adoption for increased agricultural productivity in Nigeria. Research institutes and relevant farmers' organization such as Cocoa Farmers Association of Nigeria (CFAN) and Cocoa Association of Nigeria (CAN) could organize training workshops on the adoption of intensification technologies through a participatory approach to increase cocoa yield. Government and other stakeholders could improve the supply chain of fertilizers, pesticides, and improved planting materials to broaden their use and improve their availability and affordability. The government could induce farmers to seek information through training programs and research institutes for adequate sources of information and also help to address and overcome perception barriers through engagement and information sharing.

Limitations of the study

While the research provides valuable insights into sustainable cocoa production, it is not without limitations. One key constraint is the potential scope of its geographical focus. By concentrating on Southwest Nigeria, the study may overlook variability in climate impacts and farming systems across other cocoa-producing regions in Nigeria, such as the Southeast or South–South zones, which could limit the generalizability of its findings. Additionally, the research may face challenges related to data availability and quality, a common issue in smallholder agriculture studies in developing countries. For instance, reliance on historical climate data or farmer-reported yields might introduce inaccuracies due to inconsistent record-keeping or recall bias among smallholders. To build on this research, future studies could explore several key areas. First, expanding the geographical scope to include comparative analyses across multiple cocoa-producing regions in Nigeria would enhance the understanding of how regional agroecological and climatic differences shape sustainable intensification outcomes. Second, longitudinal research over an extended period (e.g., 10–20 years) is recommended to assess the durability of intensification strategies under evolving climate scenarios, addressing the limitation of short-term perspectives.

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. AT: Data curation, Investigation, Methodology, Software, Supervision, Writing – review & editing. IO: Data curation, Investigation, Methodology, Software, Supervision, Writing – review & editing. TO: Data curation, Investigation, Methodology, Software, Supervision, Writing – review & editing. NK: Conceptualization, Data curation, Investigation, Methodology, Software, Supervision, Writing – review & editing. KE: Funding acquisition, Methodology, Project administration, Resources, Writing – review & editing. HK: Funding acquisition, Project administration, Resources, Software, Validation, Writing – review & editing. FA: Data curation, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

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 Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Adebiyi, S., and Okunlola, J. O. (2013). Factors affecting adoption of cocoa farm rehabilitation techniques in Oyo state of Nigeria. *World J. Agric. Sci.* 9, 258–265.

Adegunsoye, E. A., Tijani, A. A., and Kolapo, A. (2024). Liberalization Vis-à-Vis non-liberalization trade policy: exploring the impact of price volatility on producer share price and cocoa supply response in Nigeria and Ghana. *Heliyon* 10, 1–20.

Adeogun, S. O., Olawoye, J. E., and Akinbile, L. A. (2010). Information sources to cocoa farmers on cocoa rehabilitation techniques (CRTs) in selected states of Nigeria. *J. Media Commun. Stud.* 2, 9–15.

Afolayan, O. S. (2020). Cocoa production pattern in Nigeria: the missing link in regional agro-economic development. *An. Univ. Oradea Ser. Geogr.* 30, 88–96. doi: 10.30892/auog.301110-815

Ajayi, O. E. (2020). Sustainability of cocoa in Nigeria: Preventing the worst-case scenarios. Future Agricultures. Available online at: www.future-agricultures.org (Accessed September 18, 2023).

Akinnagbe, O. M. (2017). Impact of cocoa resuscitation programme on farmers' livelihoods in south west, Nigeria. *Agric. Conspec. Sci.* 82, 39–47.

Akinnagbe, O. M. (2020). Adoption levels of cocoa rehabilitation programmes in south West Nigeria. *Pelita Perkebunan (a Coffee and Cocoa Research Journal)* 36, 180–189. doi: 10.22302/iccri.jur.pelitaperkebunan.v36i2.396

Aneani, M., Androni, S., and Anklam, E. (2013). Determination of cocoa butter equivalents in milk chocolate by triacylglycerol profiling. *J. Agric. Food Chem.* 55, 3284–3291.

Aneani, F., and Ofori-Frimpong, K. (2013). An analysis of yield gap and some factors of cocoa (*Theobroma cacao*) yields in Ghana. *Sustain. Agric. Res.* 2:526-2016-37857.

Attipoe, S. G., Jianmin, C., and Opoku-Kwanowaa, Y. (2020). "Evaluating the Impact of Rural Finance on Cocoa Farmers Productivity: A Case Study of Bodi District in Ghana". *Asian Journal of Advances in Agricultural Research.* 12, 36–45. doi: 10.9734/ajaar/2020/v12i430092

Awoyemi, A. O., and Aderinoye-Abdulwahab, S. A. (2019). Assessment of the use of cocoa production management practices among cocoa farmers in Ekiti state, Nigeria. *Agro-Sci.* 18, 37–41. doi: 10.4314/as.v18i2.7

Babulo, B., Muys, B., Nega, F., Tollens, E. F., Nyssen, J., Deckers, J., et al. (2008). Household livelihood strategies and forest dependence in the highlands of Tigray. *Agric. Syst.* 98, 147–155.

Beckett, S. T. (2018). The science of chocolate: Edition 3. London: Royal Society of Chemistry.

Bidzakin, J., Fialor, S., Awunyo-Vitor, D., and Yahaya, I. (2019). Impact of contract farming on rice farm performance: endogenous switching regression. *Cogent Econ. Finance* 7, 1–20.

Bosompem, M., Kwarteng, J. A., and Ntifo-Siaw, E. (2011). Towards the Implementation of Precision Agriculture in Cocoa Production in Ghana: Evidence from the Cocoa High Technology Programme in the Eastern Region of Ghana. *Journal of Agricultural Research and Development.* 10, 1–9.

Caliendo, M., and Kopeinig, S. (2008). Some practical guidance for the implementation of propensity score matching. *J. Econ. Surv.* 22, 31–72. doi: 10.1111/j.1467-6419.2007.00527.x

Choudhary, M., Jat, H. S., Datta, A., Yadav, A. K., Sapkota, T. B., Mondal, S., et al. (2018). Sustainable intensification influences soil quality, biota, and productivity in cereal–based agroecosystems. *Appl. Soil Ecol.* 126, 189–198. doi: 10.1016/j.apsoil.2018.02.027

Corbeels, M., Chirat, G., Messad, S., and Thierfelder, C. (2016). Performance and sensitivity of the DSSAT crop growth model in simulating maize yield under conservation agriculture. *Eur. J. Agron.* 76, 41–53. doi: 10.1016/j.eja.2016.02.001

CRIN. (2016). Cocoa research Institute of Nigeria (CRIN)—the new cocoa hybrids. Available online at: http://www.crin-ng.org/index.php/14-crin-monthly-seminar/26-the-new-cocoa-hybrids.html (Accessed 16 October 2021).

Echendu, A. J. (2020). The impact of flooding on Nigeria's sustainable development goals (SDGs). *Ecosyst. Health Sustain.* 6:1791735. doi: 10.1080/20964129.2020.1791735

Fadeyi, O. A., Ariyawardana, A., and Aziz, A. A. (2022). Factors influencing technology adoption among smallholder farmers: a systematic review in Africa. *J Agric Rural Tropics Subtrop* 123, 13–30.

Falola, A., and Fakayode, S. B. (2014). Awareness and effects of climate change on cocoa production in Ondo state, Nigeria. *Int J Appl Agric Apic Res.* 10, 91–97.

FAO (2016). Analysis of Incentives and Disincentives for Cocoa in Nigeria. Italy: FAO.

Fawole, W. O., and Rahji, R. A. Y. (2016). Determi-nants of productivity among farmers in Ondo state of Nigeria. *Asian J. Agric. Ext. Econ. Sociol.* 20, 1–9.

Hütz-Adams, F., Huber, C., Knoke, I., Morazán, P., and Mürlebach, M. (2016). Strengthening the competitiveness of cocoa production and improving the income of cocoa producers in west and Central Africa. Bonn, Germany: Südwind.

ICCO (2019). Quarterly bulletin of cocoa statistics, vol. XLV, no.3, cocoa year 2018/19. London: International Cocoa Organisation.

IITA (2007). Towards a sustainable cocoa economy: managing rural transformation in West Africa cocoa producing communities. Ibadan: IITA.

Kamphuis, H. J. (2017). Production of cocoa mass, cocoa butter and cocoa powder. *Beckett's Ind. Chocolate Manuf. Use*, 10, 50–71. doi: 10.1002/9781118923597.ch3

Khonje, M., Manda, J., Alene, A. D., and Kassie, M. (2015). Analysis of adoption and impacts of improved maize varieties in eastern Zambia. *World Dev.* 66, 695–706. doi: 10.1016/j.worlddev.2014.09.008

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., Tijani, A. A., Olowolafe, D. E., and Muhammed, O. A. (2022). Acceptance of European Union (EU) approved pesticides for cocoa production in Nigeria. *Cogent Food Agric.* 8, 1–19.

Kumar, A., Takeshima, H., Thapa, G., Adhikari, N., Saroj, S., Karkee, M., et al. (2020). Adoption and diffusion of improved technologies and production practices in agriculture: insights from a donor-led intervention in Nepal. *Land Use Policy* 95:104621. doi: 10.1016/j.landusepol.2020.104621

Läderach, P., Martinez-Valle, A., Schroth, G., and Castro, N. (2013). Predicting the impact of climate change on the cocoa-growing regions in Ghana and Côte D'ivoire. London: Climate Change, Agriculture and Food Security, International Centre for Tropical Agriculture (CIAT).

Lawal, J. O., Omonona, B. T., Oluwatayo, I. B., Oyekale, A. S., and Salman, K. (2016). Welfare transitions and its correlates among cocoa farming households in Nigeria: an application of ordered probit approach. *Agrosearch* 16, 69–77.

McFadden, D. (1973). Conditional Logit Analysis of Qualitative Choice Behavior. In: Frontiers in Econometrics. Ed. P. Zarembka. Academic Press, 105–142.

National Population Commission (NPC) (2007) Population Figure. Federal Republic of Nigeria, Abuja. Available online at: http://www.npc.gov. (Accessed 18 March, 2021).

National Bureau of Statistics Report (2020) Nigerian Gross Domestic Product Report (2020). Available online at: http://www.nigerianstat.gov.ng/download/5l8. (Accessed May, 13, 2024).

Obuobisa-Darko, E. (2015). Socio-economic determinants of intensity of adoption of cocoa research innovations in Ghana. *Int J Afric Asian Stud.* 12, 29–41.

Oluyole, K., and Taiwo, O. (2016). Socio-economic variables and food security status of cocoa farming households in Ondo state, Nigeria. *Asian J. Agric. Ext. Econ. Sociol.* 9, 1–7. doi: 10.9734/AJAEES/2016/10077

Onubuogu, G. C., Esiobu, N. S., Nwosu, C. S., and Okereke, C. N. (2014). Resource use efficiency of smallholder cassava farmers in Owerri agricultural zone, Imo state, Nigeria. *Schol. J. Agric. Sci.* 4, 306–318.

Owolabi, K. E., and Okunlola, J. O. (2015). Farmers' utilization of indigenous knowledge techniques for the control of cocoa pests and diseases in Ekiti state, Nigeria. *Asian J. Agri. Ext. Econ. Sociol.* 4, 247–7. doi: 10.9734/AJAEES/2016/10077

Oyekale, A. S. (2017). Overview of the trend of climate change and its effects on cocoa production in Nigeria. *Am. J. Clim. Change* 6, 262–258.

Popoola, O. A., Ogunsola, G. O., and Salman, K. K. (2015). Technical efficiency of cocoa production in Southwest Nigeria. *Int J Agric Food Res* 4, 1–14. doi: 10.24102/ijafr.v4i4.583

Raters, M., and Matissek, R. (2018). Acrylamide in cocoa: a survey of acrylamide levels in cocoa and cocoa products sourced from the German market. *Eur. Food Res. Technol.* 244, 1381–1388. doi: 10.1007/s00217-018-3051-2

Rosenbaum, P. R. (2002). Observational studies. New York: Springer.

Ruf, F., Schroth, G., and Doffangui, K. (2015). Climate change, cocoa migrations, and deforestation in West Africa: what does the past tell us about the future? *Sustain. Sci.* 10, 101–111. doi: 10.1007/s11625-014-0282-4

Schroth, G., Läderach, P., Martinez-Valle, A. I., Bunn, C., and Jassogne, L. (2016). Vulnerability to climate change of cocoa in West Africa: patterns, opportunities, and limits to adaptation. *Sci. Total Environ.* 556, 231–241. doi: 10.1016/j.scitotenv.2016.03.024

Shahbandeh, M. (2021). Cocoa bean production worldwide 2018/19 & 2020/21 by country. Available online at: https://www.statista.com/statistics/263855/cocoa-bean-production-world-wide-by-region/

Sowunmi, F., Famuyiwa, G., Oluyole, K., Aroyeun, S., and Adesunloye, O. (2019). Environmental burden of fungicide application among cocoa farmers in Ondo state, Nigeria. *Sci Afric* 6:e00207. doi: 10.1016/j.sciaf.2019.e00207

Suri, T., and Udry, C. (2022). Agricultural technology in Africa. *J. Econ. Perspect.* 36, 33–56. doi: 10.1257/jep.36.1.33

Taiwo, A. O. (2016). Examining the political economy of cocoa exports in Nigeria. *Int. J. Appl. Econ. Finance* 10, 1–13. doi: 10.3923/ijaef.2016.1.13

Tijani, A., and Sofoluwe, N. (2012). Assessment of farm level pesticide use among maize farmers in Oyo state, Nigeria. *Food Sci. Qual. Manag.* 3, 1–9.

Verter, N., and Bečvářová, V. (2014). Analysis of some drivers of cocoa export in Nigeria in the era of trade liberalization. *Agris On-Line Pap. Econ. Inform.* 6, 208–218.

Wessel, M., and Foluke Quist-Wessel, P. M. (2015). Cocoa production in West Africa, a review and analysis of recent developments. *NJAS Wageningen J Life Sci* 74, 1–7. doi: 10.1016/j.njas.2015.09.001

WorldAtlas (2021) The Top 10 Cocoa Producing Countries. p. 12. Available online at: https://www.worldatlas.com (Accessed June 12, 2025).