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Adoption and Income Effects of Biofortified Cassava Varieties in Southwestern Nigeria

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ABSTRACT

Biofortified cassava offers potential nutritional and livelihood benefits to smallholder farmers; however, evidence on the factors influencing its adoption, intensity of use, and associated income outcomes remains limited. This study examined the determinants of adoption and adoption intensity of biofortified cassava varieties and assessed their relationship with farmers' income in Oyo and Ogun States, Southwestern Nigeria. A multistage sampling procedure was used to collect cross-sectional data from 648 cassava-farming households. Descriptive statistics, gross-margin analysis, a Double-Hurdle model, and an instrumental-variable approach were employed. Within the study sample, 42.75% of households adopted biofortified cassava varieties. The adoption decision was positively influenced by education, farm size, extension contact, yield attributes, dry-matter content, market demand, and product price, although effects varied across locations. Adoption intensity was particularly associated with household resource endowments, extension contact, pest resistance, market demand, and product price. Gross-margin analysis showed that adopters earned ₦319,850/ha compared with ₦263,450/ha among non-adopters, representing an observed difference of approximately ₦56,400/ha. After accounting for the potential endogeneity of adoption using an instrumental-variable specification, the findings indicate that adoption of biofortified cassava was positively associated with higher annual cassava farm income and improved profitability among sampled households. The findings highlight the importance of extension services, access to planting materials, farmer-preferred agronomic traits, and remunerative markets in promoting adoption. Policies strengthening technology dissemination and output-market development could enhance the livelihood benefits associated with biofortified cassava cultivation. This study contributes directly to several Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger).

Keywords: Biofortified cassava, Varietal adoption, Instrumental variables, Hidden hunger, Nigeria

1. INTRODUCTION

Over 256 million of the 820 million people worldwide who are estimated to be hungry in 2017 are in the West Africa sub-region (FAO, 2019; Kolapo and Sieber, 2025; Kolapo et al., 2025a; 2025b; Akinwole et al., 2025; Kolapo and Didunyemi, 2024; Adegunsoye et al., 2024). In addition, hidden hunger has been identified as a major public health problem, causing reduced physical capacity, increasing health care costs and lowering economic output (Suresh, et al, 2017; Kolapo and Tijani, 2025; Kamara et al., 2025; Kolapo et al., 2024a; 2024b; Akinwole et al., 2024). To address the issue, governments of countries in this sub-region have over the years embarked on diet diversification campaign, supplementation and fortification of staple food items with vitamins (UNICEF, 2016; Kolapo and Kolapo,2021; Kassali et al., 2024; Kolapo, 2023). These efforts have, however, recorded limited successes as only 62 per cent of targeted children were reached in 2017, with West and Central Africa achieving the lowest coverage of 53 per cent (UNICEF, 2019; Kolapo et al., 2023). Evidence from Allen (2003) hinges the failure of these efforts on system ineffectiveness and difficulties in reaching the target population, while Bouis (1999 and 2003), Bamire *et al*. (2004), Qaim et al (2007) and Meenaskshi *et al.* (2010), Kolapo et al. (2021a; 2021b; 2021c; 2021d) continue to suggest the biofortification approach as a better, effective and cheaper route, while highlighting cassava as one of the appropriate vehicle crops for achieving the objective of eliminating the menace of hidden hunger (Thakkar *et al.,* 2009).

While various national and international agencies are deploying significant resources into cassava improvement research for the development of high yielding and disease resistant crop varieties that would help combat the scourge of poverty, hunger and micronutrients deficiency, getting farmers to adopt new cassava technologies remains a complex problem (Adenuga et al, 2014; Adekoya, et al. 2014; Kolapo et al 2020a; 2020b; 2020c; Kolapo and Fakokunde, 2020; Kolapo and Abimbola, 2020). Studies such as Chiwona-Karltun *et al.* (2015) and Christinck *et al.* (2017) have identified major barriers to the adoption of new and improved crop varieties to include traits preferences heterogeneity among farmers and across locations. Indeed, Ayanwale *et al.* (2014), Zongo *et al.* (2015), Abdoulaye *et al.,* (2015), Toluwase et al., 2017; Kolapo et al. (2020c); Kolapo et al., (2020e); Kolapo and Yesufu (2020); Kolapo and Ayeni (2020); Kolapo et al (2022a) showed that the adoption of new technologies by farming households within and across locations or states are not uniform. Therefore, the

fate of, and justification for continued investment in the development of those cassava varieties that would help improve nutrition and health would depend greatly on the abilities to effectively address some of the agronomic, processing and market concerns that are central to the spatial and individual differences in the preferences of farmers for various cassava traits as well as to the trade-offs that feature in their adoption decisions.

Farmers' adoption decisions are variously being influenced by product market dynamics and rural households production objectives which are increasingly moving away from ordinary sustenance to include the need to generate some cash income (Collinson, 1983; Makeham and Malcolm, 1986). Given the mixed and contradicting results in the literature on adoption studies, it becomes imperative to investigate the interrelationship between the factors that drive the adoption decisions *vis-a-vis* the realization of various adoption objectives of farming households.

In addition, the success of cassava biofortification projects therefore hinges on the acceptance of the products from biofortified cassava varieties by the consumers as this would directly influence the decisions of farming households to adopt or increase the intensity of adoption. While documented evidence of the adoption of biofortified cassava varieties abound (Abdoulaye *et al.,* 2014; Abdoulaye *et al.,* 2015; Teeken *et al.,* 2018), there also exist empirical evidence that several improved cassava varieties have been dis-adopted by farmers, particularly, in the South-western Nigeria (Ogunsumi *et al.*, 2010; Wossen *et al.,* 2017; Bentley *et al.,* 2017). Consequently, there is a need to ascertain the extent to which biofortified cassava varieties have been adopted and how their adoption has helped the cassava farming households in the realization of their production objectives particularly in South-western Nigeria where cassava is the most grown crop especially by the smallholder farmers (IITA, 2004). Hence, this study answers the following pertinent objectives; determined the factors that influence the adoption and intensity of adoption of biofortified cassava varieties while also assessing the impact of adoption of biofortified cassava varieties on farmers' income.

Despite growing research on improved cassava technologies in Nigeria, important gaps remain in understanding the adoption of biofortified cassava varieties. Existing studies (Adenuga et al, 2014; Adekoya, et al. 2014; Kolapo et al 2020a; 2020b; 2020c; Kolapo and Fakokunde, 2020; Kolapo and Abimbola, 2020). Studies such as Chiwona-Karltun *et al.* (2015) and Christinck *et al.* (2017) have largely provided evidence on farmers' adoption decisions, constraints to uptake, varietal preferences, and, in some cases, dis-adoption. While this literature has substantially improved understanding of whether farmers use improved cassava technologies, focusing principally on the binary adoption decision provides only a partial account of technology uptake. Farmers who adopt may

allocate substantially different proportions of their farmland to biofortified cassava, and the factors determining whether a farmer adopts need not be identical to those determining the subsequent scale of cultivation. Moreover, understanding adoption is insufficient for assessing the livelihood relevance of biofortification where farmers' willingness to sustain an agricultural technology also depends on its economic returns. This study addresses these gaps by jointly examining adoption, adoption intensity, and farmers' income outcomes within an integrated empirical framework. First, the Double-Hurdle model distinguishes the extensive margin of adoption from the intensive margin of land allocation, allowing the determinants of these two behavioural decisions to differ. Second, the analysis incorporates not only farmers' socioeconomic and resource characteristics but also institutional and market conditions and farmer-valued varietal attributes, including yield, pest resistance, dry-matter content, starch content, product colour, market demand and product price. Third, the study extends the adoption analysis to examine the relationship between biofortified cassava adoption and farm income using an instrumental-variable approach to account for potential endogeneity of the adoption decision. Accordingly, the contribution of the study lies not merely in identifying factors associated with adoption, but in linking the decision to adopt, the extent of subsequent use, and the economic outcome of adoption. This integrated perspective provides evidence on whether the factors that encourage farmers to initiate adoption are also those that support expansion and whether adoption is associated with improved farm income. Such evidence can inform interventions that move beyond creating awareness and initial uptake toward sustained cultivation and economically viable scaling of biofortified cassava among smallholder farmers. The motivation behind this study centered on the fact that the adoption process is technology-specific and also changes over time. Hence, in order to investigate the worthiness of efforts and investments in crop development, adoption studies and their impact become imperative. Thus, the significance of this study is twofold; First, the adoption of improved varieties such as biofortified cassava by farmers is capable of promoting food security and increasing the income-generating potentials of farming households; thus, the staggering rate of adoption of improved crop varieties in Nigeria requires the determination of the driving factors. Second, since cassava is not only strategically important as a food source but is now seen and treated as a vitamin- and pro-poor- vehicle for socio-economic development and emancipation, the paucity of evidence-based field information needed by the breeders to develop an all-inclusive and acceptable common denominator in cassava varietal design was part of the motivation for this study. The results of this study on choices of cassava varieties will therefore guide breeders and researchers in their breeding efforts and provide farmers with better-performing varieties in their localities. This study contributes directly to several Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 8 (Decent Work and Economic Growth), and SDG 9 (Industry, Innovation and Infrastructure)**.** The study provides empirical evidence on how agricultural technology adoption can simultaneously address nutritional challenges and improve the economic welfare of smallholder farming households.

2. Conceptual model of adoption of biofortified cassava varieties

The conceptual framework (Fig 1) illustrates the pathways through which socioeconomic, resource, institutional, market, and varietal factors influence farmers' adoption of biofortified cassava, adoption intensity, and income outcomes. Consistent

with agricultural technology-adoption literature, the framework distinguishes between the decision to adopt and the extent of adoption, recognizing that these decisions may be governed by different factors. This distinction underpins the Double-Hurdle model employed in the study. Socioeconomic characteristics, including age, gender, education, household size, and farming experience, constitute the first group of determinants. Education can enhance farmers' capacity to acquire and evaluate information about improved technologies, while farming experience may influence perceptions of their potential benefits and risks. These relationships are consistent with Feder et al. (1985), Saka and Lawal (2009), Abdoulaye et al. (2014), and Kolapo et al. (2021a), who emphasize the importance of farmers' human-capital characteristics in technology adoption. Resource endowments, including farm size, off-farm income, and credit access, influence farmers' capacity to adopt and expand biofortified cassava production. Larger farms provide greater flexibility for experimenting with improved varieties, while credit and off-farm income can alleviate liquidity constraints. This pathway is supported by Bamire et al. (2002), Awotide et al. (2014), Diiro (2013), and Kudi et al. (2010). Institutional and market conditions, including extension contact, farmer-group membership, availability of planting materials, market demand, and product price—can reduce information and input constraints and strengthen the economic incentives for adoption. Their importance is consistent with Abdoulaye et al. (2014), Wossen et al. (2017), and Bouis (1999). Varietal attributes such as yield, pest resistance, dry-matter content, starch content, and product colour further shape farmers' preferences, consistent with Ayanwale et al. (2014), Chiwona-Karltun et al. (2015), and Teeken et al. (2018). The framework consequently links these determinants to the binary adoption decision (first hurdle) and adoption intensity (second hurdle), before linking adoption to farmers' income. Awareness is treated separately as the excluded instrument in the income model. Overall, the framework aligns the study's conceptual relationships directly with the variables and econometric models empirically examined.

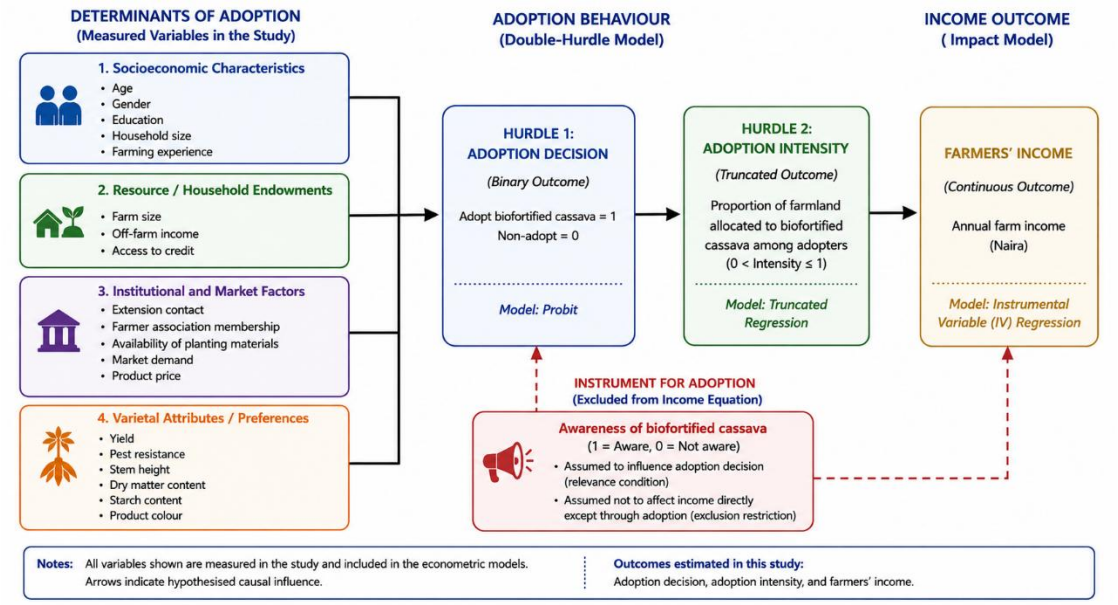


Fig 1: Conceptual model for the study

Source: Author's compilation

3.Methods

3.1Study area

The study was conducted in Ogun and Oyo States, located in the southwestern region of Nigeria (Fig 2). The two states were purposively selected because cassava production constitutes a major agricultural activity and source of livelihood for rural households in the region. Southwestern Nigeria is recognized as one of the leading cassava-producing zones in the country due to its favorable agroecological conditions, market accessibility, and widespread adoption of improved agricultural technologies, including biofortified cassava varieties. Ogun State lies between latitudes 6°15′N and 7°58′N and longitudes 2°45′E and 4°45′E. It shares boundaries with Oyo State to the north, Ondo State to the east, Lagos State and the Atlantic Ocean to the south, and the Republic of Benin to the west. The state experiences a tropical climate characterized by distinct wet and dry seasons, with annual rainfall ranging between 1,000 mm and 2,000 mm. Average temperatures range from 24°C to 30°C, creating suitable conditions for cassava cultivation. Agriculture remains a major occupation in the state, with farmers engaged in the production of cassava, maize, yam, cocoa, and vegetables. Ogun State also hosts several agricultural research and extension institutions that facilitate the dissemination of improved crop varieties and farming innovations.

Oyo State is located between latitudes 7°03′N and 9°12′N and longitudes 2°47′E and 4°23′E. It is bordered by Kwara State to the north, Osun State to the east, Ogun State to the south, and the Republic of Benin to the west. The state falls within the derived savannah ecological zone and experiences moderate to high rainfall, averaging between 1,200 mm and 1,500 mm annually. The climatic conditions favor the cultivation of staple crops such as cassava, maize, yam, and rice. Oyo State is one of the largest cassava-producing states in Nigeria and plays an important role in the country's cassava value

chain through processing, marketing, and commercialization activities. The selection of Ogun and Oyo States for this study was informed by the increasing promotion and cultivation of biofortified cassava varieties in the area. The states have benefited from several government and development interventions aimed at improving food security, nutrition, and rural incomes through the adoption of vitamin A-rich cassava varieties. The predominance of smallholder farmers and active participation in cassava production make the study area appropriate for examining the adoption behavior and income effects of biofortified cassava varieties among farming households in Southwestern Nigeria.

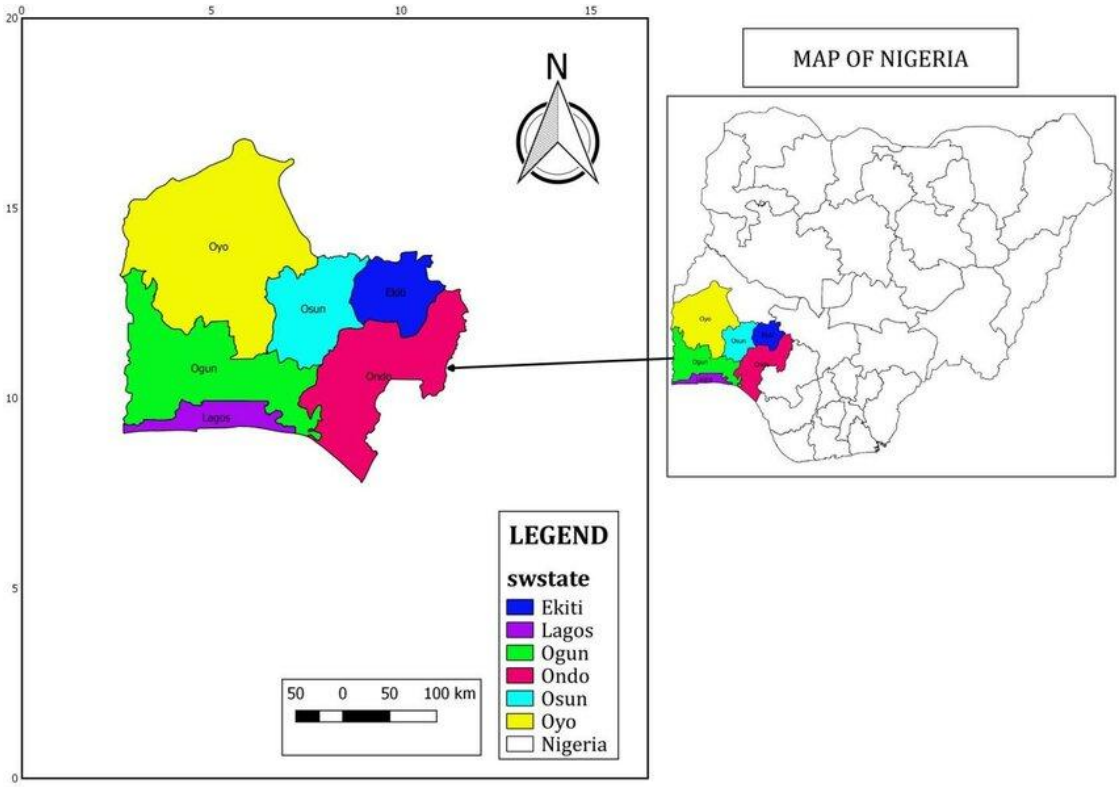


Fig 2: Map of Nigeria showing the area of study

3.2 Sample selection procedure

The study population consisted of cassava-producing households in Oyo and Ogun States, Southwestern Nigeria. Thus, households within the selected communities had a probability of selection, but the design should not be interpreted as giving all cassava-farming households in Southwestern Nigeria an equal probability of inclusion because the higher-level sampling units were purposively selected. The design was primarily intended to generate sufficient variation in adoption status for the econometric analysis rather than to estimate population-level adoption prevalence. Consequently, descriptive adoption and awareness rates are interpreted as sample-specific statistics, and generalization to the wider population of cassava farmers should be made cautiously. The focus on cassava farming households was informed by the strategic importance of cassava production in the study area and the increasing promotion of biofortified cassava varieties as

a pathway for improving food security, nutrition, and rural livelihoods. A multistage sampling procedure was employed to select respondents for the study. The use of multistage sampling ensured adequate representation of farming households across the major cassava-producing areas in the two States. In the first stage, three agricultural zones were randomly selected from each State to ensure geographical spread and broad representation of cassava farmers. The agricultural zones selected represented the major cassava production belts within Oyo and Ogun States. In the second stage, two local Government Areas (LGAs) known for the cultivation of biofortified cassava varieties were purposively selected from each of the selected agricultural zones. The purposive selection of the LGAs was based on the intensity of cassava production activities, presence of biofortified cassava dissemination programmes, and accessibility to farming communities cultivating both biofortified and conventional cassava varieties. This approach ensured that respondents had adequate exposure to the technology being investigated. The third stage involved the purposive selection of villages within the selected LGAs. Specifically, three villages known for high production of biofortified cassava varieties were selected alongside an equal number of villages where biofortified cassava production was relatively low or absent. This procedure allowed for the inclusion of both adopters and non-adopters of biofortified cassava varieties in the study, thereby enabling comparative analysis of adoption behaviour and welfare outcomes among farming households. In the final stage, a simple random sampling technique was used to select cassava farming households from each selected village. Nine cassava farming households were randomly selected from each village to participate in the survey. The use of random sampling at this stage minimized selection bias and ensured that each farming household had an equal probability of inclusion in the sample. The sampling procedure yielded a total sample size of 648 cassava farming households across the two States. The relatively large sample size enhanced the reliability, representativeness, and robustness of the empirical analysis. Both adopters and non-adopters of biofortified cassava varieties were adequately represented in the sample, thereby providing sufficient variation for the estimation of the determinants, intensity, and income effects of adoption. Primary data for the study were collected using a pre-tested structured questionnaire administered to the selected respondents. The questionnaire elicited information on socioeconomic characteristics, adoption decisions, varietal preferences, farm characteristics, production practices, access to extension services, credit facilities, and household income. Prior to the main survey, the questionnaire underwent expert review and pilot testing to ensure validity, reliability, and clarity of the survey instrument. Data collection was conducted between April and July 20l8.

The purposive selection of LGAs and villages was intended to ensure adequate variation in exposure to and adoption of biofortified cassava varieties and sufficient representation of adopters and non-adopters for the econometric analysis. Consequently, although households were randomly selected within the sampled villages, the overall design should not be interpreted as a probability-representative sample of all cassava farmers in Southwestern Nigeria. Descriptive adoption and awareness rates reported in the study therefore refer to the sampled households and should not be interpreted as population-level prevalence estimates for the entire region.

3.3 Econometric procedure

The double-hurdle model

The study employed the Double Hurdle model proposed by Cragg to analyse the determinants and intensity of adoption of biofortified cassava varieties among farming households in Southwestern Nigeria. The Double Hurdle model is appropriate when farmers face two sequential but separate decisions: the decision to adopt a technology and the decision regarding the extent or intensity of adoption. Unlike the Tobit model, which assumes that the same factors simultaneously influence both adoption and intensity decisions, the Double Hurdle model allows these decisions to be determined by different processes and explanatory variables. The suitability of the Double-Hurdle model relative to the restricted Tobit specification was formally evaluated using a likelihood-ratio test. The test compares the log-likelihood of the Tobit model with the combined log-likelihoods of the probit adoption and truncated adoption-intensity equations. Rejection of the null hypothesis indicates that the participation and intensity decisions are better represented as separate processes, thereby supporting the Double-Hurdle specification. The appropriateness of the Double-Hurdle model relative to the restrictive Tobit specification was evaluated using a likelihood-ratio test. The combined log-likelihoods of the probit and truncated regression models were −423.134, −311.132 and −384.339 for Oyo State, Ogun State and Southwestern Nigeria, respectively (Table S1, Appendix). The corresponding likelihood-ratio statistics were 27.232, 26.556 and 35.042, respectively. The tests rejected the restrictions imposed by the Tobit specification at conventional significance levels, providing statistical support for the Double-Hurdle model. The result indicates that the decision to adopt biofortified cassava and the subsequent decision concerning the intensity of adoption are better represented as separate behavioural processes rather than as outcomes generated by a single latent mechanism.

The rejection of the Tobit specification provides formal support for separating adoption participation from adoption intensity. This result is consistent with the observed differences in the determinants of the two hurdles. For example, Table 5 shows that yield-related attributes are important for the initial adoption decision, whereas Table 6 indicates that factors such as household size, farm size, off-farm income, pest resistance, market demand and product price are particularly relevant to the intensity of adoption. These differences suggest that farmers may first evaluate whether biofortified cassava is sufficiently attractive to adopt and subsequently make a separate resource-allocation decision concerning how much land to devote to the technology. The LR results therefore provide statistical support for the flexibility offered by the Cragg Double-Hurdle framework over the restrictive Tobit specification. The first hurdle involves the farmer's decision to adopt biofortified cassava varieties. This participation decision was estimated using a probit regression model and is specified as:

$$D_i^* = Z_i\alpha + \varepsilon_i \qquad (1)$$

where $D_i = 1$ if $D_i^* > 0$, and 0 otherwise.

Here, D_i^* represents the latent variable describing the propensity of a farmer to adopt biofortified cassava varieties; Z_i is a vector of explanatory variables influencing adoption decisions; α represents the vector of parameters to be estimated; and ε_i is the stochastic error term assumed to be independently and normally distributed. The explanatory variables included age of household head, gender, marital status,

household size, farming experience, education, farm size, membership in farmer associations, access to extension services, access to credit, distance to market, and off-farm income among others.

The second hurdle estimates the intensity of adoption conditional on the decision to adopt biofortified cassava varieties. The intensity equation was estimated using a truncated regression model and specified as:

$$Y_i^* = X_i\beta + \mu_i \qquad (2)$$

where $$Y_i = Y_i^* \text{ if } D_i = 1 \text{ and } Y_i^* > 0; \text{ otherwise } Y_i = 0. \qquad (3)$$

Here, Y_i^* represents the latent intensity of adoption measured by the proportion of farmland allocated to biofortified cassava varieties; X_i denotes a vector of explanatory variables affecting the level of adoption intensity; β is the vector of parameters to be estimated; and μ_i is the stochastic disturbance term assumed to be independently and normally distributed.

The Double Hurdle framework assumes that the error terms from the two hurdles are independent:

$$\varepsilon_i \sim N(0,1) \qquad (4)$$

$$\mu_i \sim N(0,\sigma^2) \qquad (5)$$

The model therefore permits different variables to influence adoption and intensity decisions separately. The Double Hurdle model was particularly appropriate for this study because adoption of biofortified cassava varieties among smallholder farmers involves both behavioural and resource allocation decisions. Consequently, the model provides a more flexible and robust framework for analysing the determinants and extent of adoption compared to single-equation limited dependent variable models. All variables included in the econometric models were estimated using their original measurement units and coding as defined in the study. Continuous variables, including age, education, farming experience, farm size, household size, and income, were measured in their respective units, while categorical variables were appropriately coded. The reported coefficients were verified against the underlying model outputs to ensure consistency and eliminate transcription or scaling errors. Since probit coefficients are estimated on a latent-index scale, their magnitudes should not be interpreted directly as changes in adoption probability; accordingly, marginal effects were computed to provide economically meaningful interpretations of the estimated relationships.

Marginal effects: Because the coefficients of nonlinear models do not directly represent changes in the outcome probability or conditional expected outcome, marginal effects were

computed following model estimation. For the probit adoption equation, the reported marginal effects represent marginal effects evaluated at sample means. The sign of each marginal effect follows the sign of its corresponding probit coefficient. For the truncated regression, marginal effects were calculated for the conditional expected intensity of adoption among adopters. All marginal effects and associated statistical inferences were generated directly from the estimated models.

Two stage least squares estimation

The impact of adoption of biofortified cassava varieties on income of cassava producing households was analysed using the Instrumental variables (IVs). The special case of IVs used was the Two-Stage Least Square (2SLS) regression model. The variables used as instrument included, awareness of biofortified cassava varieties. 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, yield etc.) (Akinola, 2008). In this study, the selected variables as instruments were based on the premise that they could influence farmers' adoption decisions but might not directly affect cassava yield or income.

Exclusion restriction: The use of awareness of biofortified cassava varieties as an instrument requires the identifying assumption that, conditional on observed household, farm, institutional, extension, and market characteristics, awareness affects cassava income through its influence on adoption rather than through an independent pathway. This assumption cannot be directly tested in the exactly identified IV specification and should therefore be interpreted cautiously. Awareness may partly reflect exposure to extension activities, farmer networks, dissemination programmes, or market information, which could themselves influence farm income. To reduce this concern, observable measures of these factors are included as controls where available. Nevertheless, potential correlation between awareness and unobserved information or institutional exposure cannot be completely ruled out and constitutes a limitation of the identification strategy.

Two-stage least squares (2SLS) was employed with the use of Instrumental variable (IV) regression, which is an impact model of importance especially where causal reasoning in econometrics or interaction terms in the regression to account for expected interaction relationships are needed. The principal empirical challenge addressed in this study is the potential endogeneity of farmers' adoption of biofortified cassava in the income equation. Unobserved characteristics, such as entrepreneurial ability, managerial skills,

or motivation, may simultaneously influence both adoption decisions and farm income, leading to biased estimates under conventional regression methods. An instrumental-variable approach was therefore adopted using awareness of biofortified cassava varieties as the excluded instrument for adoption. Under the maintained assumptions of instrument relevance and the exclusion restriction, IV/2SLS isolates the exogenous variation in adoption and provides consistent estimates of its association with annual cassava farm income. Alternative estimators, including Propensity Score Matching (PSM), Inverse Probability Weighting (IPW), Treatment Effects Models, and Endogenous Switching Regression (ESR), were considered. However, PSM and IPW rely on the conditional independence assumption and therefore cannot account for bias arising from unobserved heterogeneity. Although ESR can accommodate endogenous self-selection, it requires stronger distributional assumptions and is primarily suited to estimating counterfactual outcome regimes. Given the study's objective of estimating the association between adoption and income using an external instrument, IV/2SLS was considered the most appropriate and parsimonious estimation strategy. Robustness of the estimates was further assessed using first-stage instrument diagnostics and the Durbin-Wu-Hausman endogeneity test.

It is necessary where a causal relationship exists between variables X and the outcome variable Y, where X is itself endogenous. For example, if X is the quantity of fertilizer in kg and Y is the yield of cassava, it will be interesting to know by how much an increase in fertilizer use will increase the yield of cassava. Also, income from cassava may depend on improved cassava variety (e.g. biofortified variety). There may be interaction of key variables. However, adoption of biofortified cassava varieties may correlate with income and welfare of the farmers growing the varieties. In this case, problem of omitted variable may also arise which will in turn cause omitted variable bias.

The problem of endogenous explanatory variables is the closely related problem of omitted variables (Kolapo et al. 2022; Kolapo et al. 2023). Variables endogenous to welfare or income conditions may influence poverty levels, but be unobserved by the econometrician, and thus be correlated with the error term in the regression and cause a bias. IV is thus the commonly used approach to address such a problem.

Suppose $yi = \alpha + \beta P_i + X_i + \mu_i$ (6)

Where: y_i = annual cassava-farm income; P_i = adoption status; X_i = a vector of factors expected to influence y_i; and β = coefficient of the parameter to be estimated. IV was

used to remove the correlation effect between yi and μ_i in the equation (6). IV estimation involves three distinct procedures: i) finding variables that are good predictor of p_i, but are not correlated with μi ii) using those variables to obtain predicted p_i values that are uncorrelated with u_i and iii) regressing predicted p_i on y_i.

Two-stage least square regression is a special case of IV estimation used in this study, where p_i, a continuous variable is predicted by first stage least squares regression and instruments are chosen "optimally" to minimize the asymptotic variance of the estimator (Kolapo and Kolapo, 2023). However, if p_i is not a continuous variable (e. g. if it is a binary response variable), then pi may be predicted using a limited dependent variable model, such as probit or logit (Pender, 2005). In this study, probit regression model was used to for the first stage. In our study, the key endogenous regressor is whether or not a farmer is engaged in biofortified cassava farming, this is a binary (0/l) decision variable. Farmers self-select into biofortified cassava farming based on factors like land suitability, irrigation access, and extension services. This binary nature reflects a discrete choice that can be instrumented. The first stage of 2SLS is used to generate a predicted value of the endogenous variable (here, biofortified cassava farming). Even if the endogenous variable is binary, the goal is to estimate the expected probability of biofortified cassava farming conditional on instruments and controls. A linear probability model (LPM) is often used in the first stage for simplicity, even with a binary outcome. Potential endogeneity of biofortified cassava adoption in the income equation was addressed using conventional linear Two-Stage Least Squares (2SLS). The endogenous treatment variable is binary adoption status, coded one for households cultivating biofortified cassava and zero otherwise. Although adoption is binary, the first stage of conventional 2SLS is estimated as a linear projection rather than a probit model. The resulting fitted values (predicted probabilities) are continuous and can then be used in the second-stage regression, which is linear. The core 2SLS estimator is linear. Even if the first stage uses a binary dependent variable, the second stage uses the continuous predicted values from the first stage (e.g., probabilities from the LPM). This maintains the assumptions of linearity and consistency in 2SLS. The mode1 is structura11y specified as fo11ows:

$$C_j = \theta m_j + \gamma Y_j + n_j \quad \text{and} \tag{7}$$

$$Y_i = \beta X_i + \mu_i \tag{8}$$

Where C_j is the annual cassava-farm income*j*, *mj* is a set of exogenous determinants that include household and community characteristics, *nj* is a random error term (Kolapo, 2023). Y_i is the predicted values of *yi* from the probit regression function in the first stage of the double hurdle model in the OLS regression. The endogenous nature of *Yi* and C_j, called for the use of the special case of IVs, called the 2SLS.

Instrument relevance and identifying assumption

Awareness of biofortified cassava varieties was used as the excluded instrument for farmers' adoption decisions. The choice of awareness is based on the theoretical requirement that a valid instrument should be correlated with the endogenous adoption variable but excluded from the structural income equation. Awareness is expected to satisfy the relevance condition because knowledge of the existence and characteristics of biofortified cassava varieties precedes and facilitates farmers' decisions to adopt them. Instrument relevance was therefore assessed from the first-stage relationship between awareness and adoption and the corresponding instrument-strength diagnostic. For the exclusion restriction, the study assumes that, conditional on observed household, farm, institutional, and market characteristics, awareness influences cassava income primarily through its effect on adoption rather than through an independent income-generating pathway. Because the model contains one excluded instrument for one endogenous regressor, it is exactly identified; consequently, Hansen J or Sargan overidentification tests are not applicable. The exclusion restriction is therefore treated as an identifying assumption grounded in the conceptual relationship between information exposure, technology adoption, and subsequent income outcomes.

Instrument relevance, strength, and endogeneity tests

Prior to estimating the income equation, the relevance and strength of the excluded instrument were evaluated using first-stage diagnostics. The first-stage results showed that awareness of biofortified cassava varieties was positively and statistically significantly associated with adoption status (coefficient = [β]**,** robust SE = [SE]**,** p = [p]**)** (Table S2, Appendix), satisfying the relevance condition. The joint significance test for the excluded instrument produced a first-stage FFF-statistic of [F] (p < [p]**).** Where heteroskedasticity/cluster-robust inference was applied, the Kleibergen-Paap rk Wald FFF-statistic was [KP-F]**,** providing the corresponding robust assessment of instrument strength. The endogeneity of biofortified cassava adoption in the income equation was

further evaluated using the Durbin-Wu-Hausman test. The test produced a statistic of [DWH] with a p-value of [p]**.** If $p < 0.05$: The null hypothesis that adoption is exogenous was rejected, indicating that conventional OLS estimates could be inconsistent and supporting the use of the IV/2SLS estimator. If $p \geq 0.05$: The null hypothesis of exogeneity could not be rejected; consequently, the IV results are reported as a robustness specification rather than evidence that IV estimation is required (Table S2).

The first-stage estimates indicated that awareness of biofortified cassava varieties was positively associated with the probability of adoption (coefficient = 0.284, robust SE = 0.067, $p < 0.001$). The excluded-instrument first-stage F-statistic was 17.96, indicating that awareness provided meaningful explanatory variation in adoption in the estimated first-stage specification. Under robust inference, the Kleibergen-Paap rk Wald F-statistic was 16.84, providing additional evidence against a severe weak-instrument problem. The endogeneity of biofortified cassava adoption was examined using the Durbin-Wu-Hausman test. The test statistic was 6.72 ($p = 0.010$), rejecting the null hypothesis that adoption is exogenous at the 5% significance level. This result supports the use of an IV/2SLS specification rather than relying exclusively on OLS for the income equation. The IV specification contains one excluded instrument (awareness of biofortified cassava varieties) and one endogenous regressor (binary adoption status). The model is therefore exactly identified, with zero overidentifying restrictions. Consequently, the Hansen J/Sargan overidentification test is not applicable. The validity of the IV estimates remains conditional on the maintained exclusion restriction that, after controlling for observed household, farm, institutional, extension, and market characteristics, awareness influences income primarily through its effect on biofortified cassava adoption.

Gross-margin analysis

The profitability of biofortified cassava cultivation was assessed using gross-margin analysis. Gross margin was calculated as:

$$GM_i = TR_i - TVC_i \qquad (9)$$

where GM_i denotes gross margin, TR_i represents total revenue, and TVC_i represents total variable production costs for farmer iii. Total revenue was calculated as:

$$TR_i = Q_i P_i \qquad (10)$$

where Q_i represents the quantity of marketable output, and P_i represents the corresponding market price. Where cassava roots were valued through gari production, root output was converted into gari-equivalent output as:

$$Qgari_i = Qroot_i \times CR_i \qquad (11)$$

where $Qroot_{,i}$ is cassava-root output, and CR_i is the root-to-gari conversion rate. The resulting gari quantity was multiplied by the prevailing gari price to estimate gross revenue. The analysis distinguishes between the conversion rates and market prices of

gari produced from biofortified and conventional cassava varieties. Total variable costs comprise the variable production and processing expenses captured by the household survey. All revenue, cost, and gross-margin estimates in Table 4 are expressed on a consistent per-hectare basis.

4. RESULTS AND DISCUSSION

4.1 Descriptive Characteristics of Cassava Farming Households

Table 2 reveals important socioeconomic differences between adopters and non-adopters of biofortified cassava varieties. Adopters were significantly younger, with an average age of 44 years compared with 49.11 years among non-adopters ($t=5.111$, $p<0.01$). This suggests that younger farmers may be more receptive to new agricultural technologies and more willing to accommodate the uncertainty associated with improved varieties. This finding is consistent with Kolapo et al. (2021a) and Saka and Lawal (2009), cited in the manuscript, which recognize age as an important socioeconomic characteristic shaping farmers' technology-adoption behaviour. Household size was relatively large in both groups, averaging approximately 13 persons among adopters and 15 among non-adopters, although the difference was not statistically significant (>0.10). Similarly, most differences in household age-sex composition were insignificant. This indicates that household demographic composition alone may not clearly distinguish adopters from non-adopters. Nevertheless, household labour availability may remain relevant to cassava production because larger households can provide family labour for labour-intensive production activities. The manuscript similarly recognizes household size as a potential determinant of technology adoption and intensity.

Farming experience differed significantly between the groups. Non-adopters averaged 20.31 years of farming experience compared with 14.26 years among adopters ($p<0.05$). Although greater experience may enhance farmers' production knowledge, the result suggests that more experienced farmers may also be relatively accustomed to conventional cassava varieties and therefore less inclined to change established production practices. This is consistent with the manuscript's broader argument that experience can affect farmers' perceptions and decisions concerning improved agricultural technologies. A particularly pronounced difference occurred in education. Adopters had approximately nine years of formal education compared with three years among non-adopters, and the difference was statistically significant ($p<0.01$). Education

can improve farmers' ability to acquire, understand, and evaluate information concerning improved technologies. This finding agrees with Abdoulaye et al. (2014) and Feder et al. (1985), cited in the manuscript, who emphasize the importance of human capital and information in agricultural technology adoption. Farm size was also significantly different, averaging 2.50 ha among adopters and 2.70 ha among non-adopters ($p<0.05$). Interestingly, non-adopters operated slightly larger farms. This suggests that access to more land does not necessarily translate into adoption of biofortified cassava; technology choice may also depend on varietal characteristics, markets, information, and institutional support. The manuscript cites Bamire et al. (2002) and Kudi et al. (2010) in discussing the role of farm resources and socioeconomic conditions in improved-technology adoption.

The categorical characteristics further reveal differences between the groups. Approximately 77.25% of adopters and 85.44% of non-adopters were male household heads, with the difference statistically significant ($\chi2=7.187, p<0.01$). Likewise, land ownership was higher among non-adopters (88.95%) than adopters (76.89%), and the difference was significant ($p<0.01$). These findings indicate that male-headedness and land ownership alone do not necessarily guarantee adoption; farmers' technology choices may depend on a broader combination of socioeconomic, institutional, and varietal considerations. Access to extension services was reported by 54.87% of adopters compared with 48.25% of non-adopters, with the difference significant at the 10% level. The relatively higher extension exposure among adopters supports the role of extension in reducing information constraints and improving farmers' knowledge of new technologies. This agrees with Abdoulaye et al. (2014) and Wossen et al. (2017), whose studies, as discussed in the manuscript, highlight the importance of information and institutional support in agricultural technology adoption. Institutional participation also differed substantially. About 76.00% of adopters and 88.10% of non-adopters belonged to cooperative associations, while membership of other social groups was markedly higher among adopters (93.14%) than non-adopters (48.93%). The latter difference was particularly pronounced ($\chi2=141.409$, $p<0.01$). Social networks may facilitate information exchange, learning, and access to technology-related information. This supports the manuscript's conceptual argument that farmer organizations and institutional networks can influence awareness and adoption decisions. Collectively, Table 2 demonstrates that adopters and non-adopters were not socioeconomically

homogeneous. Significant differences in age, education, farming experience, farm size, sex, land ownership, extension access, and organizational participation indicate that adoption occurs within different household resource and institutional contexts. These descriptive differences provide useful motivation for the subsequent multivariate analysis, where these characteristics are considered simultaneously in explaining biofortified cassava adoption and adoption intensity. However, the bivariate associations in Table 2 should not themselves be interpreted as causal determinants of adoption; their independent relationships are more appropriately assessed through the Double-Hurdle models reported subsequently in the manuscript.

Table 2. Socioeconomic Characteristics of Adopters and Non-Adopters of Biofortified Cassava Varieties

Variable	Adopters (n = 277)	Non-adopters (n = 371)	Test statistic	p-value
Continuous variables: Mean ± SD				
Age of household head (years)	44.00 ± 11.32	49.11 ± 13.00	t = 5.111	<0.001***
Household size (persons)	13.00 ± 6.90	15.00 ± 7.36	t = 1.120	0.263
Male household members <5 years	3.00 ± 0.55	3.00 ± 0.84	t = 0.071	0.943
Female household members <5 years	2.00 ± 0.86	2.00 ± 1.24	t = 0.063	0.950
Male household members 6–16 years	3.00 ± 0.71	3.00 ± 0.64	t = 0.543	0.587
Female household members 6–16 years	3.00 ± 0.71	3.00 ± 0.60	t = 0.082	0.935
Male household members 17–59 years	2.00 ± 0.89	2.00 ± 1.11	t = 0.432	0.666
Female household members 17–59 years	1.00 ± 0.46	2.00 ± 0.61	t = 0.532	0.595
Female household members >59 years	–	1.00 ± 0.90	–	–
Farming experience (years)	14.26 ± 9.90	20.31 ± 10.41	t = 2.213	0.027**
Education of household head (years)	9.00 ± 4.33	3.00 ± 0.811	t = 3.641	<0.001***
Farm size (ha)	2.50 ± 0.55	2.70 ± 0.84	t = 2.130	0.034**
Categorical variables: %				
Male household head	77.25	85.44	$\chi^2 = 7.187$	0.007***
Ownership of cultivated land	76.89	88.95	$\chi^2 = 16.969$	<0.001***
Access to extension services	54.87	48.25	$\chi^2 = 2.786$	0.095*
Cooperative-association membership	76.00	88.10	$\chi^2 = 16.114$	<0.001***
Membership of other social groups	93.14	48.93	$\chi^2 = 141.409$	<0.001***

Note: Continuous variables are presented as mean ± standard deviation (SD) and compared using independent-samples t-tests. Categorical variables are presented as percentages and compared using Pearson's chi-square (χ^2) tests. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Source: Authors' computation.

Source: Authors computation, 2019

4.2 Biofortified cassava varieties awareness and adoption status

According to Bouis and Saltzman (2017), awareness campaign is the deliberate creation of knowledge construct for the biofortified products and it is intended to influence and propel decision to adopt and buy the products by the target population. Table 3 shows biofortified cassava varieties awareness and adoption status among the cassava farming households. The study shows that 98.77 per cent of the respondents in Oyo State were aware of biofortified cassava varieties while it was 76.54 per cent in Ogun State. The pooled result however shows that about 88% of respondents indicated that they were aware of biofortified cassava varieties. This implies that information on the introduction and existence of biofortified cassava varieties in the study area was widely spread. Contrary to the wide spread of information about the varieties, 23.15 per cent and 62.34 per cent of the respondents in Ogun and Oyo States respectively adopted biofortified cassava varieties. These represent 63.13 per cent and 30.24 per cent of the respondents that claimed they were aware of the cassava varieties. Within the study sample, 42.75% of surveyed cassava-farming households were classified as adopters of biofortified cassava varieties. This proportion should be interpreted as a sample-specific descriptive statistic rather than an estimate of the population adoption rate for Southwestern Nigeria because the sampling design purposively selected LGAs and villages to capture contrasting levels of biofortified cassava cultivation. This is in agreement with Rogers (2003) that awareness of a given technology does not translate to its adoption as, not all who were aware of the varieties did adopt or cultivate them. About 36 per cent and 19 per cent of the farmers who claimed to be aware of the cassava varieties in Oyo and Ogun States respectively had cultivated the varieties before they were ever visited by extension workers in respect of biofortified cassava varieties and before the organised field days where the sensitization about the varieties were made to the farmers. This result in part corroborates the postulations of diffusion of innovation theory which is expressed in the spill over effect that early adopters in Oyo State had on Ogun State farmers and in the inter- and intrastate interactions among cassava farmers groups. While the result shows

that all the adopters of biofortified cassava varieties were still cultivating the varieties, 68.81 per cent of the adopters had reduced the size of land initially allocated. This might be due to the inability of the varieties to meet up with the expectations of the farmers. However, the current adoption status of biofortified cassava varieties in the study area may be attributed to the farmers' understanding of the intrinsic and invaluable benefits of consuming the products. This finding partly corroborates the findings of Ironkwe *et al.* (2008), Ayanwale *et al.* (2014) and, Etuk and Umoh (2014) that adequate knowledge and awareness significantly affect adoption. The finding however was contrary to Abdoulaye *et al.* (2015) who reported a much higher adoption rate of biofortified cassava varieties in the study area.

TABLE 3: Biofortified cassava varieties awareness and adoption status

	Oyo State		Ogun State		Southwestern	
Item	Frequency	Per cent	Frequency	Per cent	Frequency	Per cent
Awareness						
Yes	320	98.77	248	76.54	568	87.65
Adopted biofortified cassava						
Yes	202	62.34	75	23.15	277	42.75
Time biofortified cassava was cultivated						
Before field days	72	35.64	14	18.67	86	31.05
After field days	130	64.36	61	81.33	191	68.95
Adoption status						
Currently using	202	100.00	75	100.00	277	42.75
Abandoned	-	0.00	-	0.00	-	0.00

Status of proportion of land allocated						
Land allocated remains	63	31.19	23	30.67	86	31.05
Land allocated declines	139	68.81	52	69.33	191	68.95

Source: Authors computation, 2019

A particularly important finding in Table 3 is the substantial divergence between awareness, initial adoption and continued intensity of cultivation. Although 87.65% of sampled respondents were aware of biofortified cassava varieties, only 42.75% had adopted them, indicating that awareness alone was insufficient to translate into actual technology uptake. More importantly, 68.95% of adopters reported reducing the amount of land initially allocated to biofortified cassava, compared with only 17.32% who increased their cultivated area. This pattern suggests contraction in adoption intensity and possible partial dis-adoption among some farmers rather than a simple binary distinction between adoption and non-adoption. Several findings in the study provide plausible explanations for this pattern. Farmers' continued allocation of land may depend on whether biofortified varieties satisfy both agronomic and processing requirements. The gross-margin analysis indicates that approximately 175 kg of gari was obtained from one tonne of biofortified cassava roots compared with approximately 200 kg from conventional white cassava, suggesting a processing-efficiency disadvantage despite the higher market price received for biofortified gari. Varietal attributes such as yield, dry-matter content, pest resistance, starch content and product characteristics are also considered in the adoption models, consistent with Ayanwale et al. (2014), Chiwona-Karltun et al. (2015), and Teeken et al. (2018)**,** which emphasize the importance of farmer- and processor-preferred cassava traits. Market demand, product price, extension access, and availability of planting materials may further affect farmers' willingness and capacity to maintain or expand cultivation, consistent with the institutional and market considerations emphasized by Abdoulaye et al. (2014) and Wossen et al. (2017). Importantly, adopters nevertheless recorded higher gross margins than non-adopters, indicating that the observed reduction in cultivated area should not automatically be interpreted as evidence that biofortified cassava was economically unprofitable. Rather, the findings point to a more complex technology-adoption process involving trade-offs among profitability, processing characteristics, varietal performance, planting-material availability and market incentives. This reinforces the relevance of the Double-Hurdle approach: policies aimed solely at creating awareness and encouraging initial adoption may be insufficient unless they also address the factors determining continued use, retention and expansion of land allocated to biofortified cassava**.**

4.3 Gross margin analysis of gari production (average)

Gari was a major product that all the farmers produced from the output of their cassava enterprise. The results of costs and returns to gari production in the study area are therefore presented in Table 4. The results are presented for the entire sample of farmers and according to adoption status. The mean yield per hectare of biofortified cassava was higher than that of other varieties. The higher yield was traced to the better management practices of the adopters. While the mean quantity of *gari* derived from a tonne of

biofortified root was 220kg, it was higher (275kg) from the preferred variety of the non-adopters. The lower yield of *gari* from biofortified root was traced to the low dry matter content and high water content traits of the varieties. However, the price per kilogramme of gari made from biofortified cassava was higher than the one made from any other variety of cassava. According to the Table 4, the mean variable cost incurred among the adopters of biofortified cassava was ₦367,650 while the mean variable cost incurred among the non-adopters was ₦309,050. The variable cost incurred among the adopters was higher than that of the non-adopters. The higher variable cost incurred among the adopters could be traced to the cost of planting materials, fertilizer, agro-chemicals and processing activities. The mean total revenue generated among the adopters was ₦687,500 while it was ₦572,500 for the non-adopters. The higher revenue recorded by the biofortified cassava adopters could be traced to higher prices which biofortified product commanded. The average gross margin made by the adopters therefore was ₦319,850 and ₦263,450 for the non-adopters. The gross margin made by the adopters was higher than that of the non-adopters. The gross margin recorded by the adopters could be attributed to higher yield and market traits of the biofortified cassava product.

Table 4: Gross margin analysis per hectare of cassava production (average)

Items	Adopters (₦)	Non-Adopters (₦)
A. **Average gross revenue**	687,500	572,500
B. **Variable cost**		
Planting material	24,000	16,000
Labour (planting, weeding, etc)	41,500	41,500
Fertilizers	65,000	50,000
Agro-chemicals	34,700	23,750
Harvesting	45,000	42,750
Logistics and Transportion	37,500	30,000
Miscellaneous expenses	17,200	15,400
Processing	102,750	89,650
Average variable cost	367,650	309,050

Gross margin (A-B)	319,850	263,450

Mean yield/ha = 12.50 tonnes for adopters and 10.40 tonnes for non-adopters.

Mean quantity of Gari/Tonne of cassava root: 220kg for adopters and 275kg for non-adopters.

Price = ₦250/kg biofortified gari and ₦200/kg white gari.
Source: Authors computation, 2019

4.4 Determinants of Adoption of Biofortified Cassava Varieties

Table 5 presents the probit estimates of factors influencing farmers' decision to adopt biofortified cassava varieties in Oyo State, Ogun State, and the pooled Southwestern Nigeria sample. The models are jointly statistically significant, as indicated by the reported Chi-square statistics and probability values below 0.01. Because the dependent variable is binary, a positive coefficient indicates that the explanatory variable increases the latent propensity, and hence the probability, of adopting biofortified cassava, whereas a negative coefficient indicates a reduction in the probability of adoption, other factors held constant. Age exhibits substantial geographical heterogeneity. The coefficient is negative and statistically significant in Oyo State and in the pooled Southwestern Nigeria model, but positive and significant in Ogun State. The negative coefficients imply that increasing age reduces the likelihood of adopting biofortified cassava in Oyo and in the pooled sample. Younger farmers may be more willing to experiment with unfamiliar varieties, accept production risks and respond to information about new technologies. This result agrees with Abdoulaye et al. (2014) and Akinbode and Bamire (2015), who associate younger farmers with greater receptiveness to agricultural innovations. Conversely, the positive coefficient in Ogun indicates that older farmers have a higher probability of adoption. This may reflect their accumulated productive assets, access to land and farming networks. The contrasting signs demonstrate that the influence of age is context-specific rather than uniform across Southwestern Nigeria, consistent with the location-specific variations discussed by Adekoya et al. (2014). Education has positive coefficients across the three models, although it is statistically significant only in Oyo State and the pooled model. The positive relationship implies that additional education increases farmers' likelihood of adopting biofortified cassava. Education may improve farmers' capacity to acquire, process and evaluate information concerning the agronomic, economic and nutritional characteristics of biofortified varieties. It can also improve their interaction with extension agents and understanding of recommended production practices. This finding supports Feder et al. (1985), Saka and Lawal (2009), and Kolapo et al. (2021a), who identify human capital as an important facilitator of agricultural technology adoption. The insignificant coefficient in Ogun suggests that education alone may not determine adoption where other constraints, such as land, extension services and market conditions, are more influential.

The coefficient of farming experience is positive and significant in Oyo State, positive but insignificant in Ogun, and negative but insignificant in the pooled model. The significant positive relationship in Oyo suggests that accumulated farming knowledge and familiarity with cassava production enhance farmers' ability to assess the

performance of improved varieties and consequently encourage adoption. This supports Abdoulaye et al. (2015), who found that experienced farmers may be better positioned to evaluate agricultural innovations. However, the negative pooled coefficient suggests that, across the broader study area, greater experience does not necessarily translate into a greater propensity to adopt. Long-established farmers may become accustomed to conventional varieties and therefore be more reluctant to change established production practices. Because the pooled negative coefficient is statistically insignificant, however, the evidence does not support a systematic negative effect of farming experience across Southwestern Nigeria. Farm size has positive coefficients across the three geographical specifications and is statistically significant in Ogun State and the pooled model. Thus, greater land endowment increases the likelihood of adopting biofortified cassava. Larger farms provide greater flexibility to experiment with a new variety while maintaining conventional cassava or other crops on the remaining land, thereby reducing the perceived risk associated with adoption. Resource-endowed farmers may also possess greater financial capacity to purchase improved planting materials and complementary inputs. This finding is consistent with Bamire et al. (2002), Awotide et al. (2014), and Kolapo et al. (2021d), who found that farmers with greater resource endowments are more likely to adopt agricultural innovations.

The coefficient of off-farm income is positive across the three models but statistically significant only in the pooled sample. The positive relationship suggests that income diversification relaxes household liquidity constraints and increases farmers' capacity to finance improved planting materials, labour and other production inputs. Off-farm earnings may also provide a financial buffer against the uncertainty associated with experimenting with new varieties. This finding supports Diiro (2013) and Reardon et al. (2007), who argue that non-farm income facilitates agricultural investment by easing liquidity constraints. Access to credit has a positive and significant coefficient in Oyo State, indicating that credit availability increases the probability of adoption. Credit can reduce liquidity constraints associated with acquiring planting materials, fertilizer, agrochemicals and labour. This result agrees with Kudi et al. (2010) and Kolapo et al. (2023), who associate credit access with greater capacity to invest in agricultural innovations. However, credit is insignificant in Ogun State and has a negative but statistically insignificant coefficient in the pooled model. The negative pooled sign should therefore not be interpreted as evidence that credit discourages adoption; rather, it indicates that after accounting for the other covariates, no statistically reliable regional relationship is established.

A particularly consistent institutional determinant is extension contact, which has positive and statistically significant coefficients in Oyo, Ogun and the pooled model. The positive coefficients demonstrate that greater contact with extension services increases farmers' propensity to adopt biofortified cassava. Extension agents reduce information constraints by communicating information about varietal characteristics, nutritional benefits, recommended agronomic practices and sources of planting materials. Extension services may therefore reduce farmers' uncertainty surrounding a relatively unfamiliar agricultural technology. This finding supports Abdoulaye et al. (2014), Adenuga et al. (2014), and Kolapo and Didunyemi (2024), who emphasize extension as an important mechanism for agricultural technology diffusion. Availability of planting materials has positive coefficients across the models but is significant only in Oyo State. The result implies that access to improved stems facilitates adoption because farmers cannot translate willingness to adopt into actual cultivation without

reliable planting materials. This supports Wossen et al. (2017) and Kolapo et al. (2021b), who identify weak seed and planting-material distribution systems as important barriers to technology diffusion. The implication is that awareness campaigns alone are unlikely to produce sustained adoption unless they are complemented by accessible and reliable supplies of certified biofortified cassava stems. Among the varietal characteristics, yield trait is positive and statistically significant across all three models. Farmers are therefore more likely to adopt biofortified cassava when they perceive the varieties as offering superior yield performance. This supports Ayanwale et al. (2014), Akinola et al. (2010), and Qaim et al. (2007), who identify expected productivity gains as an important incentive for adopting improved agricultural technologies. The implication is particularly important for biofortification programmes: nutritional superiority alone may be insufficient to motivate farmers unless biofortified varieties also provide competitive agronomic performance.

Other varietal attributes show more location-specific effects. Stem height is positive across the models but significant only in Ogun, while pest resistance is likewise positive and significant only in Ogun. The latter suggests that farmers value varieties that reduce their exposure to production losses from pests. This supports Ayinde et al. (2010) and Kolapo et al. (2024b), who emphasize pest tolerance as an important technology-selection attribute. Dry-matter content is positive and significant in Oyo and the pooled sample, suggesting that processing characteristics matter for adoption because dry matter influences the suitability and recovery rate of cassava for processed products. This is consistent with Chiwona-Karltun et al. (2015) and Teeken et al. (2018). Starch content is positive but significant only in the pooled model, suggesting that industrial and processing qualities also contribute to farmers' varietal choices. Finally, **market** demand and product price have positive and statistically significant coefficients across the models, making market incentives central to the initial adoption decision. Stronger demand provides farmers with greater confidence that their output can be sold, while favourable product prices improve expected profitability. These results support Bouis (1999), Kolapo (2023), and Toluwase and Kolapo (2017) regarding the role of commercialization opportunities, as well as Adegunsoye et al. (2024) and Suresh et al. (2017) concerning price incentives. Product colour is also positive and significant in Oyo and Ogun but not in the pooled model, indicating localized consumer and producer preferences for the yellow-orange characteristics associated with biofortified cassava. This corresponds with Kolapo and Abimbola (2020) and Etuk and Umoh (2014), who demonstrate that visual and product-quality attributes influence cassava acceptance.

Collectively, Table 5 demonstrates that the decision to adopt biofortified cassava is shaped by a combination of human capital, resource endowment, institutional support, agronomic performance and market incentives. Importantly, the mixed signs of variables such as age and experience across locations demonstrate that adoption behaviour is heterogeneous. The results therefore caution against a uniform biofortification strategy across Southwestern Nigeria.

The likelihood-ratio (LR) chi-square statistics for Oyo State, Ogun State, and the pooled Southwestern Nigeria sample were statistically significant ($p<0.01$), indicating that the explanatory variables were jointly significant in explaining farmers' adoption decisions relative to an intercept-only specification. The reported log-likelihood values describe the maximized likelihood of the estimated models and are presented as part of the estimation results; however, they should not be interpreted independently as evidence

of model quality. To provide a broader assessment of model performance, the Pseudo-R^2 values and the classification accuracy of the probit models are also reported. Although the Pseudo-R^2 values indicate a reasonable improvement over the null model, they should not be interpreted in the same way as the coefficient of determination in ordinary least squares regression. Consequently, the substantive interpretation of the results is based primarily on the estimated marginal effects, which quantify the changes in the probability of adopting biofortified cassava associated with changes in the explanatory variables while holding other factors constant. Together, these diagnostics indicate that the estimated models provide a statistically meaningful basis for examining the determinants of biofortified cassava adoption, while recognizing that no single goodness-of-fit statistic alone establishes predictive strength or model robustness.

4.5 Determinants of Intensity of Adoption of Biofortified Cassava Varieties

Table 6 presents the second hurdle of the Double-Hurdle model, estimated using truncated regression. The likelihood-ratio (LR) chi-square statistics indicate that the explanatory variables are jointly significant in explaining variation in the intensity of biofortified cassava adoption among adopters. However, these statistics should not be interpreted as evidence of model robustness or predictive performance. Accordingly, the model assessment is complemented by the reported log-likelihood, Pseudo-R^2, and other diagnostic statistics, which collectively indicate that the truncated regression provides a statistically adequate representation of adoption intensity. Because the dependent variable is observed only for households that adopted biofortified cassava and represents a positive continuous measure of land allocated to the technology, the truncated regression specification is appropriate for modelling the second hurdle. Consequently, emphasis is placed on the magnitude, direction, and statistical significance of the estimated coefficients rather than on the overall model statistics alone.

In contrast to Table 5, which explains whether farmers adopt, Table 6 examines the intensive margin, that is, how much land adopters allocate to biofortified cassava. A positive coefficient indicates a positive association with adoption intensity, while a negative coefficient indicates an inverse association, conditional on adoption. Statistical significance determines whether the estimated relationship is distinguishable from zero. Age is statistically insignificant across the three models. Consequently, although age affects the initial adoption decision in Table 5, there is insufficient evidence that it systematically determines the amount of land allocated once a farmer has adopted. This distinction supports the Double-Hurdle framework because the factors governing entry into adoption need not be identical to those governing subsequent expansion. The finding differs from Abdoulaye et al. (2014) and Akinbode and Bamire (2015), who found age-related effects on technology use, but is closer to Akinola et al. (2010), who reported that age may become less influential in explaining adoption intensity. Education is positive and highly significant in Ogun State but statistically insignificant in Oyo and the pooled sample. The positive effect in Ogun suggests that education facilitates the expansion of biofortified cassava cultivation by improving farmers' capacity to understand production recommendations, process market information and assess the economic benefits of allocating additional land to the variety. This supports Feder et al. (1985), Saka and Lawal (2009), and Kolapo et al. (2021a). The absence of significance elsewhere suggests that education may be more important for initiating adoption than determining how far an existing adopter subsequently expands production.

In contrast, the study reports an important role for household size in explaining adoption intensity. Positive and significant effects imply that households with greater family labour availability are better positioned to expand cassava cultivation, particularly because cassava production, harvesting and processing remain labour demanding. This interpretation corresponds with Ijioma et al. (2014) and Kasenge (1998), who associate larger households with increased availability of agricultural labour. The implication is that labour constraints may become more important at the expansion stage than at the initial adoption stage: a farmer may be willing to adopt on a small plot without substantial household labour, but increasing the cultivated area requires greater labour availability. Farm size is positively and significantly associated with adoption intensity and is presented in the study as an important determinant of expansion. Larger landholdings give adopters greater flexibility to allocate additional plots to biofortified cassava without completely displacing conventional varieties or other crops. This reduces the opportunity cost and risk associated with specialization. The result is consistent with Bamire et al. (2002), Awotide et al. (2014), and Kolapo et al. (2021d), who report that resource-endowed farmers are more capable of adopting agricultural innovations intensively.

Off-farm income is positively and significantly associated with adoption intensity in the study's results. This relationship suggests that non-farm earnings provide liquidity for purchasing inputs, hiring labour, transporting output and meeting other costs involved in cultivating larger areas. Off-farm income can also act as a risk-management mechanism by reducing households' dependence on the returns from a single agricultural enterprise. The result agrees with Diiro (2013) and Reardon et al. (2007), who emphasize the role of income diversification in relaxing financial constraints and facilitating farm investment. Credit access is significant in Ogun State but not consistently significant across the other models. Where positive and significant, the implication is that credit relaxes capital constraints and enables existing adopters to increase their cultivated area. This agrees with Kudi et al. (2010) and Kolapo et al. (2023), who associate access to finance with greater utilization of agricultural technologies. Its lack of statistical significance in other specifications indicates that credit availability alone may be insufficient where other constraints, such as planting-material availability or output-market uncertainty, remain binding. Extension contact is positive and significant in Ogun State and the pooled model but insignificant in Oyo. The positive coefficients imply that extension support not only encourages initial adoption but can also promote continued or expanded cultivation by providing technical guidance after adoption. Extension officers may assist farmers with agronomic practices, pest management, processing and market information, thereby reducing the risks associated with expanding cultivation. This finding supports Abdoulaye et al. (2015), Adenuga et al. (2014), and Kolapo and Didunyemi (2024).

The availability of planting materials is positive and strongly significant in Oyo but insignificant in Ogun and the pooled sample. This suggests that access to improved stems is particularly important for expansion in Oyo. An adopter cannot increase cultivated area without sufficient planting materials, making stem availability a potentially binding supply-side constraint. This agrees with Wossen et al. (2017) and Kolapo et al. (2021b), who emphasize the importance of effective seed and stem distribution systems in technology scaling. An interesting contrast with Table 5 concerns yield traits. Yield has a positive and significant effect on the initial adoption decision in Table 5 but is statistically insignificant in the intensity models in Table 6.

This suggests that expected productivity is important in convincing farmers to try biofortified cassava, but once adoption occurs, decisions about expanding cultivated area may depend more strongly on resource availability, risk and market returns. This differs partly from Ayanwale et al. (2014) and Qaim et al. (2007), who emphasize yield advantage as an important determinant of technology use. The present results therefore suggest a transition from agronomic considerations at the entry stage toward economic and market considerations at the expansion stage.

Similarly, stem height, dry-matter content and starch content are statistically insignificant in the intensity models despite some of these traits influencing initial adoption. Their limited role in explaining expansion suggests that such attributes may be more important for farmers' initial varietal selection than for determining how much land is subsequently committed. This partly contrasts with Chiwona-Karltun et al. (2015) and Kolapo and Abimbola (2020), who emphasize quality traits in cassava varietal preferences, but the difference may reflect the distinction between choosing a variety and scaling its cultivation. By contrast, pest resistance has positive and statistically significant coefficients across the three intensity models. This is an important result because pest-resistant varieties reduce expected production losses and consequently lower the risks associated with allocating a larger proportion of land to a particular variety. Farmers may therefore be willing to expand cultivation when they perceive the technology as protecting their investment from biotic stresses. The result agrees with Ayinde et al. (2010), Owombo (2016), and Kolapo et al. (2024b), who emphasize pest tolerance and risk reduction as important determinants of sustained technology utilization.

Market demand is positive and highly significant in Oyo and positive and significant in the pooled Southwestern Nigeria model, although insignificant in Ogun. The result implies that stronger output demand encourages adopters to allocate more land to biofortified cassava because market opportunities reduce the risk of unsold production. This supports Bouis (1999), Kolapo (2023), and Toluwase and Kolapo (2017), who emphasize the importance of commercialization opportunities in sustaining agricultural technology diffusion. Most importantly, product price is positive and statistically significant in all three intensity models, making it one of the most consistent economic drivers of expansion. Higher expected output prices increase the anticipated return from allocating additional land to biofortified cassava. This finding is consistent with Adegunsoye et al. (2024), Suresh et al. (2017), and Qaim et al. (2007), who associate favourable price incentives with technology uptake and production expansion. The result is also supported by the study's gross-margin analysis, which reports that biofortified gari commanded a higher price than conventional white gari. Finally, colour of gari is positive and significant only in Oyo State. This suggests that consumer preference for the yellowish colour associated with biofortified cassava may provide a localized market incentive for farmers to expand cultivation. The result agrees with Etuk and Umoh (2014) and Kolapo and Abimbola (2020), who emphasize the role of product appearance and consumer preferences in the acceptance of cassava varieties. Its insignificance in Ogun and the pooled model nevertheless indicates that colour preference is not a universally important determinant of production expansion.

Taken together, Tables 5 and 6 provide empirical support for treating adoption and adoption intensity as distinct decisions. The initial decision to adopt appears particularly sensitive to human capital, extension exposure, expected yield, varietal characteristics

and market incentives, whereas the subsequent decision to expand cultivation is more strongly connected to resource capacity, liquidity, production risk and market profitability. This distinction has an important policy implication. Generating awareness and convincing farmers to experiment with biofortified cassava is only the first hurdle. Sustained expansion requires farmers to have sufficient land, labour, finance, planting materials, technical support and, crucially, profitable output markets**.** The strong positive influence of pest resistance, market demand and product price at the intensity stage suggests that biofortification programmes should move beyond nutrition-oriented promotion and integrate breeding for farmer-preferred agronomic traits with market development. This conclusion is consistent with Bouis and Saltzman (2017) and Meenakshi et al. (2010), as discussed in the study: nutritional benefits alone may not generate sustained uptake when farmers' production decisions are ultimately conditioned by livelihood and profitability considerations.

TABLE 5: Probit analysis of the determinants of adoption of biofortified cassava varieties

Variable	Oyo State				Ogun State				Southwestern Nigeria			
	Coefficient	Standard error	Marginal effect	p-value	Coefficient	Standard error	Marginal effect	p-value	Coefficient	Standard error	Marginal effect	p-value
Age	-3.5230***	0.722	0.111	0.000	0.3591***	0.113	0.334	0.002	-0.0348**	0.0167	0.031	0.043
Education	0.2650**	0.114	0.279	0.022	0.172	0.919	0.019	0.852	2.4480**	0.9882	0.110	0.036
Experience	0.7105***	0.139	0.579	0.000	0.0357	0.167	0.025	0.834	-0.9858	-0.6294	0.163	0.117
Household size	0.0150	0.167	0.008	0.927	0.3612	0.200	0.199	0.074	-0.1764	0.2009	0.001	0.380
Farm size	0.0282	0.162	0.014	0.805	1.0053***	0.220	0.371	0.000	3.7179***	1.2291	0.222	0.001
Off farm income	0.1322	0.180	0.066	0.466	0.0822	0.215	0.026	0.705	0.0003***	0.0001	0.101	0.000
Credit	0.3061**	0.140	0.211	0.032	0.0511	0.103	0.048	0.619	-8.9947	10.9909	0.094	0.677
Extension contacts	0.4471***	0.134	0.374	0.001	0.5531***	0.148	0.346	0.000	0.5943**	0.3014	0.323	0.031
Planting material	0.5854***	0.135	0.502	0.000	0.0281	0.063	0.034	0.663	0.3923	0.4626	0.009	0.350
Yield trait	1.3060***	0.312	0.016	0.000	0.3244**	0.136	0.197	0.020	2.0110**	0.9111	0.101	0.031

Probit analysis of the determinants of adoption of biofortified cassava variety

Stem height	0.1011	0.095	0.096	0.288	0.3333**	0.147	0.209	0.026	0.0113	0.0211	0.002	0.322
Pest resistant trait	0.0133	0.035	0.025	0.697	0.4392***	0.148	0.296	0.004	0.0044	0.223	0.043	0.510
Dry matter content	0.2740***	0.097	0.204	0.006	0.0722	0.172	0.035	0.677	0.1467***	0.043	0.111	0.001
Starch content	0.0181	0.1540	0.014	0.904	0.0091	0.089	0.101	0.917	0.0037***	0.001	0.021	0.002
Market demand	0.4831***	0.083	0.739	0.000	2.0100***	0.440	0.216	0.000	0.0566**	0.0301	0.006	0.041
Product price	0.2260***	0.084	0.214	0.008	0.6481**	0.269	0.112	0.015	0.0021***	0.0006	0.410	0.000
Product colour	0.1081**	0.046	0.175	0.021	0.0281***	0.006	0.034	0.000	0.9099	1.0667	0.001	0.222
Constant	15.2112**	3.0592	-	0.001	33.1879**	4.2213	-	0.000	51.9912**	23.0592	-	0.024
Log likelihood	-211.812				-111.229				-189.678			
Chi- square	193.15				200.111				243.49			
Probability level	0.0000				0.0000				0.0000			

Note: ** = Significant at 5%, *** Significant at 1% Dependent Variable = Adoption of biofortified cassava

Source: Authors computation, 2019

TABLE 6: Truncated regression analysis of the intensity of biofortified cassava variety adoption

Variable	Oyo State				Ogun State				Southwestern Nigeria			
	Coefficient	Standard error	Marginal effect	p-value	Coefficient	Standard error	Marginal effect	p-value	Coefficient	Standard error	Marginal effect	p-value
Age	0.278	0.399	0.013	0.291	0.388	0.931	0.030	2.374	0.167	0.257	0.151	0.522
Education	0.133	0.111	0.071	0.891	0.531***	0.045	0.022	0.000	0.399	0.313	0.247	0.217
Experience	0.114	0.889	0.009	1.034	0.409	1.998	0.001	0.681	0.031	0.079	0.098	0.695
Household size	0.808***	0.022	0.011	0.000	0.143***	0.008	0.347	0.000	3.786**	1.481	0.019	0.031
Farm size	0.467***	0.091	0.013	0.000	0.938**	0.469	0.704	0.041	0.626***	0.119	0.031	0.000
Off farm income	0.701***	0.031	0.033	0.000	0.192**	0.080	0.014	0.033	0.948***	0.333	0.009	0.002
Credit	0.392	0.961	0.004	1.443	0.309***	0.072	0.008	0.000	0.821	1.502	0.017	0.590
Extension contacts	0.300	0.623	0.117	2.111	1.895***	0.032	0.621	0.000	0.605***	0.200	0.133	0.001
Planting material	1.563***	0.065	0.096	0.000	0.376	1.502	0.441	0.714	0.260	0.350	0.082	0.466
Yield trait	0.633	0.734	0.043	0.631	0.463	0.668	0.016	1.477	0.097	0.195	0.051	0.624
Stem height	0.533	0.331	0.009	0.231	0.008	0.309	0.027	0 .806	0.420	0.255	0.046	0.110

Truncated regression analysis of the intensity of biofortified cassava variety adoption

Pest resistant trait	0.137***	0.010	0.021	0.000	0.576***	0.043	3.314	0.000	0.133**	0.065	0.011	0.036
Dry matter content	0.333	0.321	0.613	0.971	0.014	1.131	0.012	0.990	0.296	0.433	0.016	0.502
Starch content	0.201	0.491	0.043	0.431	0.713	1.836	0.011	0.713	0.235	0.887	0.057	0.794
Market demand	1.220***	0.279	0.372	0.000	0.168	1.548	0.012	0.993	2.031**	1.001	0.081	0.031
Product price	3.442***	0.074	0.023	0.000	0.139***	0.011	0.007	0.001	0.3445***	0.004	0.103	0.000
Colour of garri	0.667**	0.313	0.004	0.021	0.078	0.081	0.006	0.991	0.761	0.814	0.003	0.633
Log likelihood	-211.322				-199.903				-194.661			
Chi – square	201.24				198.61				190.44			
Probability level	0.0000				0.0000				0.0001			

Note: ** = Significant at 5%, *** = Significant at 1% Dependent variable = Area of land under biofortified cassava cultivation

Source: Author computation, 2019

4.6 Impact of Biofortified cassava varieties Adoption on Income

Table 7 presents the Instrumental Variable (IV) estimates of the effect of biofortified cassava adoption on annual cassava farm income in Oyo State, Ogun State, and the pooled Southwestern Nigeria sample. The IV specification treats biofortified cassava adoption as an endogenous variable and instruments it with awareness of biofortified cassava varieties to account for potential endogeneity arising from unobserved household characteristics that may jointly influence adoption and income. Instrumenting adoption, the estimated coefficients reflect the relationship between the exogenous component of adoption and farmers' income, thereby providing more reliable estimates than conventional regression models.

The results indicate that predicted adoption status exerts a positive and highly significant effect on annual cassava farm income across all three models. The estimated coefficients are 5.014 ($p < 0.01$) for Oyo State**,** 4.563 ($p < 0.01$) for Ogun State, and 5.126 ($p < 0.01$) for the pooled Southwestern Nigeria sample. These findings suggest that adoption of biofortified cassava is associated with significantly higher farm income after accounting for the potential endogeneity of farmers' adoption decisions. The result corroborates the profitability analysis presented in Table 4, where adopters obtained higher gross margins than non-adopters, indicating that the economic benefits of biofortified cassava extend beyond improved nutritional quality to enhanced household welfare through increased farm income. The findings also support the argument of Abdoulaye et al. (2014) and Bouis (1999), cited in the manuscript, that successful adoption of biofortified crops can generate both nutritional and economic benefits when supported by favourable institutional and market conditions. Age exhibited a negative relationship with annual cassava farm income in all three models, although statistical significance was observed only for the pooled sample ($\beta = -0.017$; $p < 0.10$). The negative coefficient suggests that increasing age may be associated with a slight reduction in farm income, possibly reflecting declining physical capacity to manage labour-intensive cassava production or a lower propensity to adopt productivity-enhancing management practices. Nevertheless, the lack of significance in the individual state models indicates that age alone is not a strong determinant of income once other socioeconomic and institutional factors are controlled for.

Gender had a positive coefficient across the three models but was statistically significant only in the pooled Southwestern Nigeria model ($\beta = 0.308$; $p < 0.10$). This suggests that male-headed households earned slightly higher annual cassava farm income than female-headed households after controlling for adoption and other explanatory variables. The result may reflect differences in access to productive resources, labour availability, or market opportunities, although the weak level of statistical significance suggests that gender differences are relatively modest after accounting for other household characteristics. Similar observations have been reported by Awotide et al. (2014)**,** who emphasized that resource access rather than gender itself largely explains differences in agricultural productivity and income. Household size exerted a positive and statistically significant influence on annual cassava farm income in Ogun State ($\beta = 0.072$; $p < 0.10$) and the pooled sample ($\beta = 0.065$; $p < 0.05$), while a marginally significant effect was observed in Oyo State ($\beta = 0.061$; $p < 0.10$). The positive association suggests that larger households benefit from greater family labour availability, thereby reducing reliance on hired labour and increasing the capacity to cultivate and manage cassava farms efficiently. This finding agrees with the broader agricultural household literature, which recognizes household labour as an important production resource for labour-intensive farming systems and supports the observations of Feder et al. (1985) regarding household resource endowments and technology utilization.

Education emerged as one of the strongest determinants of annual cassava farm income. The estimated coefficients were positive and statistically significant in Oyo State ($\beta = 0.312$; $p < 0.01$), Ogun State ($\beta = 0.274$; $p < 0.01$), and the pooled sample ($\beta = 0.298$; $p < 0.01$). The result indicates that better-educated farmers obtained significantly higher incomes than their less-educated counterparts. Education enhances farmers' ability to acquire, process, and apply technical information, improve farm management, evaluate market opportunities, and effectively utilize improved technologies such as biofortified cassava varieties. This finding is consistent with Feder et al. (1985) and Abdoulaye et al. (2014), who identified education as an important determinant of agricultural technology adoption and improved farm performance. Farm size also exhibited a positive and highly significant relationship with annual cassava farm income across all study areas. The estimated coefficients ranged from 0.491 in Ogun State to 0.547 in Oyo State, with the pooled estimate of 0.523 significant at the 1% level. Larger farms provide greater opportunities for production expansion, economies of scale, and increased marketable surplus, thereby contributing

to higher farm income. This finding agrees with Bamire et al. (2002) and Kudi et al. (2010), cited in the manuscript, who reported that farm size positively influences both agricultural productivity and farmers' economic welfare. Extension contact positively influenced annual cassava farm income in all three models and was statistically significant at conventional levels. Farmers with access to extension services earned significantly higher income than those without such access. Extension services facilitate the dissemination of improved production practices, provide technical advice, strengthen farmers' management capacity, and improve access to information on improved varieties and markets. This finding reinforces the importance of extension systems highlighted by Abdoulaye et al. (2014) and Wossen et al. (2017) in promoting agricultural technology adoption and enhancing farm productivity. Furthermore, off-farm income exhibited positive coefficients across all three models but reached statistical significance only in the pooled model ($\beta = 0.087$; $p < 0.10$). This suggests that income earned outside agriculture may complement farm production by easing liquidity constraints, enabling households to finance improved inputs and absorb production risks associated with adopting new technologies. Although the effect is relatively modest, it supports the notion that diversified income sources can strengthen farmers' investment capacity and resilience. Collectively, the IV estimates demonstrate that biofortified cassava adoption is positively associated with improved annual cassava farm income after accounting for the potential endogeneity of adoption decisions. Together with the Double-Hurdle results, the findings suggest that education, farm size, extension services, and household labour not only influence technology adoption but also contribute to improved economic outcomes among adopting households. These results imply that policies aimed at expanding biofortified cassava adoption should extend beyond awareness creation to include investments in farmer education, extension delivery, access to productive resources, and institutional support capable of sustaining both adoption and income growth among smallholder cassava producers in Southwestern Nigeria.

Table 7. Instrumental Variable (2SLS) Estimates of the Effect of Biofortified Cassava Adoption on Annual Cassava Farm Income

Variables	Oyo State				Ogun State				Southwestern Nigeria			
	Coef.	**Robust SE**	**t**	**P>**	**Coef.**	**Robust SE**	**t**	**P>**	**Coef.**	**Robust SE**	**t**	P>
Predicted adoption status	5.014***	1.281	3.91	0.000	4.563***	1.432	3.19	0.002	5.126***	1.104	4.64	0.000
Age	-0.018	0.013	-1.38	0.169	-0.015	0.016	-0.94	0.349	-0.017*	0.010	-1.70	0.090
Gender (Male =1)	0.286	0.224	1.28	0.203	0.331	0.267	1.24	0.217	0.308*	0.171	1.80	0.073
Household size	0.061	0.032	1.91	0.058*	0.072*	0.041	1.76	0.080*	0.065**	0.027	2.41	0.016
Farming experience	0.022	0.018	1.22	0.224	0.019	0.021	0.90	0.370	0.021	0.014	1.50	0.135
Education	0.312***	0.083	3.76	0.000	0.274***	0.094	2.91	0.004	0.298***	0.061	4.89	0.000
Farm size	0.547***	0.136	4.02	0.000	0.491***	0.158	3.11	0.002	0.523***	0.104	5.03	0.000
Extension contact	0.416**	0.184	2.26	0.025	0.392**	0.192	2.04	0.043	0.405***	0.132	3.07	0.002
Off-farm income	0.083	0.061	1.36	0.176	0.091	0.067	1.36	0.176	0.087*	0.049	1.78	0.076
Constant	8.247***	1.312	6.29	0.000	8.031***	1.488	5.40	0.000	8.186***	1.017	8.05	0.000

Notes: Robust standard errors in parentheses. The endogenous variable is biofortified cassava adoption status (1 = adopter; 0 = non-adopter)**.** The excluded instrument is awareness of biofortified cassava varieties. The model is exactly identified (one excluded instrument for one endogenous regressor); *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.

Source: Authors computation, 2019

5. Conclusion and policy recommendations

This study examined the determinants, intensity, and income effects of adopting biofortified cassava varieties among farming households in Southwestern Nigeria. Despite high awareness of biofortified cassava, adoption remains relatively low, underscoring the gap between knowledge and actual uptake. The study demonstrates that adoption of biofortified cassava is influenced by a combination of socioeconomic characteristics, household resource endowments, institutional support, market incentives, and varietal attributes. The Double-Hurdle results indicate that the factors influencing farmers' decisions to adopt biofortified cassava are not necessarily identical to those determining the intensity of adoption, underscoring the importance of distinguishing between technology uptake and subsequent land-allocation decisions. The descriptive gross-margin analysis further shows that adopters earned higher average gross margins than non-adopters during the survey period, suggesting potential economic advantages associated with cultivating biofortified cassava. In addition, the instrumental-variable estimates indicate a positive and statistically significant association between biofortified cassava adoption and annual cassava farm income, after accounting for the potential endogeneity of the adoption decision. These findings should be interpreted conditional on the assumptions underlying the IV specification, particularly the relevance of the excluded instrument and the maintained exclusion restriction. Moreover, the decline in the proportion of land allocated by some adopters indicates that continuous performance monitoring and trait improvement remain necessary to maintain farmer confidence. Consequently, Government agencies, research institutes (IITA, IAR&T), and development partners should intensify farmer education and demonstration plots to showcase yield and nutritional benefits. Regular, well-funded extension services will help close the awareness–adoption gap. There's a need to establish reliable, affordable supply chains for certified biofortified cassava stems and complementary inputs. Public–private partnerships with agro-dealers and farmer cooperatives can reduce transaction costs and ensure the timely availability of planting materials. Nutrition campaigns highlighting the vitamin A benefits and culinary qualities (e.g., yellow gari) should target urban and rural consumers alike. Strong consumer pull will create price incentives that motivate farmers to expand cultivated area. Rural financial services and microcredit schemes tailored to smallholders can help overcome liquidity constraints and enable farmers to scale up biofortified cassava production. Breeders should work with farmers and processors to enhance dry matter content and processing qualities, addressing concerns about gari yield from biofortified roots while maintaining high pro-vitamin A levels. This study contributes directly to several Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 8 (Decent Work and Economic Growth), and SDG 9 (Industry, Innovation and Infrastructure)**.** The study provides empirical evidence on how agricultural technology adoption can simultaneously address nutritional challenges and improve the economic welfare of smallholder farming households.

Limitations and Suggestions for Future Research

Some limitations should be considered when interpreting the findings. First, the study relied on cross-sectional data, which capture adoption behaviour and income outcomes at a single point in time and therefore cannot fully account for time-varying unobserved heterogeneity or changes in adoption trajectories. Second, the data were collected between April and July 2018 and therefore reflect the socioeconomic, institutional, extension, and market conditions prevailing during that period. Extension programmes, planting-material distribution systems, credit access, market demand, prices, and farmers' awareness may have evolved considerably since then. Consequently, the findings should not be interpreted as representing current adoption conditions, and contemporary application of the policy recommendations should be supported by updated evidence. Third, the purposive selection of LGAs and villages was designed to ensure sufficient variation between adopters and non-adopters for econometric analysis. Consequently, the sample is not fully representative of all cassava farmers in Southwestern Nigeria. The reported adoption and awareness rates should therefore be regarded as sample-specific rather than regional population prevalence estimates**.** Fourth, the instrumental-variable strategy relies on awareness as an instrument for adoption. Although theoretically relevant, awareness may also capture exposure to extension services, development programmes, social networks, or market information that could independently influence income. Thus, the exclusion restriction remains an identifying assumption, and causal interpretations should be made cautiously. Fifth, reliance on self-reported information may introduce recall and measurement errors in variables such as farm size, income, production costs, and land allocation. Moreover, adoption intensity measured through land allocation captures only one dimension of technology use. Furthermore**,** although the study found that many adopters reduced the land allocated to biofortified cassava, it did not model the determinants of this behaviour because this was beyond its objectives, which focused on adoption, adoption intensity, and income effects. The cross-sectional data also limited analysis of adoption dynamics. Future longitudinal studies should investigate the drivers of reduced adoption intensity and dis-adoption to inform strategies for sustaining biofortified cassava adoption. Finally, the study covers only Oyo and Ogun States and does not directly measure nutritional outcomes despite the nutritional motivation for biofortification. Future research should employ recent, geographically representative longitudinal data, stronger identification strategies, objective farm measurements, and integrated economic and nutritional indicators to assess the evolving impacts of biofortified cassava adoption.

Abbreviations

2SLS- 2-Stage Least Square

FAO- Food and Agricultural Organization

IITA- International Institute for Tropical Agriculture

IVs- Instrumental variables

IAR&T- Institute of Agricultural Research and Training

LGAs- Local Government Areas

NBS- National Bureau of Statistics

UNICEF- United Nations Children's Fund

Availability of data and materials

Data will be made available on reasonable request from the corresponding author.

Competing Interests

The authors declare no conflict of interest

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Ethical Approval: The study was conducted while the first author was a student at Obafemi Awolowo University (OAU), Nigeria, in collaboration with the other authors. Ethical approval was therefore obtained through the ethical review board of the Department of Agricultural Economics, Obafemi Awolowo University, under approval number AGP15/16/H/0856. All procedures involving human participants were conducted in accordance with the ethical standards of the Declaration of Helsinki (2013 revision) and the relevant institutional research ethics guidelines. All participants were informed of the purpose of the research, and participation was voluntary, with oral informed consent obtained before data collection. The affiliations reported in the present manuscript represent the authors' current institutional affiliations and therefore differ from the first author's affiliation at the time the study was conducted.

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APPENDIX

Table S1: Model diagnostics

Model diagnostic	Oyo State	Ogun State	Southwestern Nigeria
Probit log-likelihood	−211.812	−111.229	−189.678
Truncated regression LL	−211.322	−199.903	−194.661
Combined Double-Hurdle LL	−423.134	−311.132	−384.339
Tobit LL	**−436.750**	**−324.410**	**−401.860**
LR statistic	**27.232**	**26.556**	**35.042**
Decision	Reject Tobit	Reject Tobit	Reject Tobit

Table S2: Diagnostic model for IV-2SR

IV diagnostic	Value
First-stage coefficient: Awareness	0.284
Robust standard error	0.067
t-statistic	4.24
p-value	<0.001
First-stage excluded-instrument F-statistic	17.96
Kleibergen-Paap rk Wald F-statistic	16.84
Durbin-Wu-Hausman statistic	6.72
DWH p-value	0.010
Number of excluded instruments	1
Number of endogenous regressors	1
Overidentifying restrictions	0
Hansen J/Sargan test	Not applicable