Magna Scientia Advanced Research and Reviews

eISSN: 2582-9394

Cross Ref DOI: 10.30574/msarr

Journal homepage: https://magnascientiapub.com/journals/msarr/

(Research Article)

Determinants of Adoption and Technical Efficiency of Biofortified Crops among Smallholder Farmers in North-Central Nigeria

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Magna Scientia Advanced Research and Reviews, 2021, 03(02), 108-121

Publication history: Received on 10 November 2021; revised on 23 December 2021; accepted on 25 December 2021

Article DOI: https://doi.org/10.30574/msarr.2021.3.2.0091

Abstract

Biofortified crops have emerged as a critical innovation for addressing micronutrient deficiencies and improving food security across sub-Saharan Africa. In Nigeria, where malnutrition remains prevalent, biofortified varieties of maize, cassava, and sweet potato offer potential pathways for enhancing dietary quality while improving smallholder productivity. Yet, adoption among rural farming households is uneven, and understanding the determinants of adoption alongside the technical efficiency of producers is essential for scaling these innovations. This study examines the factors influencing adoption and technical efficiency of biofortified crops among smallholder farmers in North-Central Nigeria. Using cross-sectional survey data combined with stochastic frontier analysis, the research identifies household socioeconomic characteristics, access to extension services, credit availability, and awareness campaigns as key drivers of adoption decisions. Findings indicate that education, farm size, and participation in farmer-based organizations significantly increase the likelihood of adopting biofortified varieties. In terms of efficiency, results show that adopters of biofortified crops achieve higher output per unit of input compared to non-adopters, highlighting the productivity benefits of improved varieties. However, inefficiency persists due to constraints such as limited access to quality seed, poor storage facilities, and inadequate market linkages. Policy implications underscore the need for strengthening extension services, promoting credit schemes tailored for smallholders, and integrating biofortified crops into government-led food and nutrition programs. By addressing both adoption determinants and efficiency constraints, stakeholders can enhance the dual role of biofortified crops in reducing malnutrition and increasing farm-level productivity, contributing to broader food security goals in Nigeria.

Keywords: Biofortified crops; Adoption determinants; Technical efficiency; Smallholder farmers; North-Central Nigeria; Food security

1. Introduction

1.1. Background and Context

Malnutrition remains a persistent public health challenge in Nigeria, with micronutrient deficiencies particularly widespread among vulnerable groups such as women and children [1]. Vitamin A deficiency, iron deficiency anemia, and zinc insufficiency have been identified as major contributors to stunted growth, weakened immunity, and poor cognitive outcomes [2]. These deficiencies reduce labor productivity and impose significant economic costs, linking nutrition directly to development outcomes [3]. Addressing malnutrition therefore requires strategies that extend beyond supplementation and fortification, embedding solutions into agricultural systems themselves.

Biofortified crops have emerged as an innovative, nutrition-sensitive approach to this challenge. Developed through conventional breeding techniques or biotechnology, these crops are enriched with higher levels of essential

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micronutrients, such as vitamin A in cassava, orange-fleshed sweet potato, and maize [4]. They offer a sustainable pathway to improving diets, as they integrate seamlessly into local food cultures and farming systems [5]. For smallholder farmers, biofortified crops also present an opportunity to diversify production while enhancing resilience to food and nutrition insecurity.

In Nigeria, biofortification initiatives have been promoted by both government agencies and international research organizations, with North-Central states playing a prominent role in pilot projects [3]. However, adoption has varied widely, raising questions about the technical efficiency of production and the factors that shape uptake. Understanding this context is essential to positioning biofortified crops as both a nutrition and livelihood innovation [6].

1.2. Research Problem and Rationale

Despite the promise of biofortification, adoption levels remain uneven across farming households in North-Central Nigeria. While some farmers have embraced crops such as vitamin A maize or biofortified cassava, others remain hesitant, citing barriers such as seed availability, yield uncertainty, and inadequate extension support [7]. These gaps limit the nutritional impact of biofortification programs, reducing their ability to significantly alleviate micronutrient deficiencies at scale [3].

Productivity outcomes also remain inconsistent. Although biofortified crops are designed to match or exceed yields of conventional varieties, variations in soil quality, input use, and knowledge of improved practices often affect technical efficiency [2]. This underscores the importance of evaluating not only whether farmers adopt, but also how effectively they manage production once adoption occurs.

North-Central Nigeria represents a particularly relevant case study. The region is a major agricultural zone, characterized by smallholder-dominated farming, mixed crop-livestock systems, and high prevalence of malnutrition [8]. Furthermore, it has been the focus of significant biofortification interventions, making it a strategic area for understanding adoption patterns and productivity dynamics [7]. Investigating this context provides critical insights for scaling biofortification across Nigeria and sub-Saharan Africa [1].

1.3. Structure of the Article

This article is organized to provide a coherent and comprehensive analysis of adoption and technical efficiency of biofortified crops in North-Central Nigeria. Following this introduction, Section 2 reviews the theoretical and empirical literature on biofortification, adoption models, and efficiency measurement approaches [6]. Section 3 presents the study area and methodology, detailing sampling procedures, data collection techniques, and econometric models used for analysis.

Section 4 reports findings on adoption determinants, highlighting socioeconomic, institutional, and farm-level factors shaping farmer decisions [5]. Section 5 evaluates technical efficiency levels across adopters and non-adopters, drawing on stochastic frontier models to identify drivers of efficiency gaps [7]. Section 6 discusses implications for nutrition security, agricultural extension, and policy design, emphasizing opportunities for scaling biofortification programs [8]. Finally, Section 7 concludes with recommendations for policymakers, practitioners, and researchers, while also outlining areas for further study [2]. This structure ensures a seamless flow from problem framing to evidence-based solutions.

2. Conceptual framework and literature review

2.1. Biofortification and Nutrition Security

Biofortification has emerged as a strategic response to global malnutrition, particularly in regions where dietary diversity is limited and supplementation programs face logistical barriers [8]. By enriching staple crops with essential vitamins and minerals through plant breeding, biofortification addresses “hidden hunger,” the chronic deficiencies of micronutrients like vitamin A, iron, and zinc. Unlike fortification, which adds nutrients during food processing, biofortification delivers nutrition at the farm level, making it particularly relevant for rural populations reliant on subsistence production [11].

Globally, biofortification initiatives have demonstrated success in increasing nutrient intake and improving health outcomes. For example, orange-fleshed sweet potatoes in East Africa have significantly raised vitamin A consumption among women and children [9]. Similarly, iron-biofortified beans in Latin America and South Asia have been linked to improved hemoglobin levels and reduced anemia prevalence [13]. These experiences highlight biofortification as a scalable and cost-effective intervention in the global nutrition agenda [7].

In Nigeria, the introduction of biofortified crops such as vitamin A maize, cassava, and sweet potatoes reflects both the urgency of addressing malnutrition and the promise of nutrition-sensitive agriculture [12]. Programs led by HarvestPlus and national agricultural research institutes have advanced awareness, seed dissemination, and extension support, especially in North-Central states. Yet, adoption remains inconsistent, shaped by factors including seed accessibility, yield perception, and cultural preferences. Bridging these gaps is central to transforming biofortification from a pilot innovation into a mainstream agricultural solution [10]. Thus, examining both adoption and technical efficiency is critical for understanding how biofortification can improve nutrition security in Nigeria.

2.2. Technology Adoption Theories in Smallholder Contexts

The adoption of agricultural innovations has long been studied through theoretical frameworks that illuminate how farmers evaluate, accept, or reject new technologies. Rogers' Diffusion of Innovations theory emphasizes attributes such as relative advantage, compatibility, complexity, trialability, and observability as key determinants of adoption behavior [7]. These dimensions remain relevant for understanding biofortified crops, which must be perceived as beneficial not only nutritionally but also agronomically by smallholders.

Beyond diffusion theory, behavioral and economic models enrich understanding of farmer decision-making. The Theory of Planned Behavior highlights attitudes, social norms, and perceived control as critical drivers of adoption decisions [12]. Farmers often weigh social acceptability such as community perceptions of orange or yellow grain varieties alongside profitability when choosing whether to adopt biofortified crops [10]. Similarly, the Utility Maximization framework underscores the role of risk, expected yield, and market access in shaping adoption choices [9].

In smallholder contexts, structural constraints such as limited credit, weak extension systems, and uncertain input markets often condition adoption outcomes [13]. Agricultural adoption models in developing countries increasingly integrate socio-demographic variables (e.g., age, gender, education), institutional access (extension services, cooperatives), and agroecological factors (soil fertility, rainfall) [11]. For biofortified crops in Nigeria, adoption cannot be fully explained by awareness alone; rather, a multidimensional lens is required, considering both behavioral motivations and structural limitations [8]. This blend of theories provides a conceptual foundation for analyzing how and why smallholders adopt or fail to adopt biofortified crops in North-Central Nigeria.

2.3. Technical Efficiency and Productivity in Smallholder Systems

Beyond adoption, technical efficiency is central to understanding the productivity outcomes of biofortified crops. Technical efficiency reflects the ability of farmers to maximize output from a given set of inputs, serving as a benchmark for productivity performance [13]. Smallholder systems, often characterized by resource constraints, typically exhibit significant efficiency gaps, meaning output falls short of potential due to suboptimal practices, knowledge gaps, or infrastructural barriers [7].

Analytical approaches such as the Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA) have been widely applied to measure efficiency in agricultural systems. SFA distinguishes inefficiency from random shocks by modeling deviations from a frontier production function, while DEA uses linear programming to assess relative efficiency among farmers [12]. Both methods have been employed in Nigerian agriculture to evaluate crops like maize, cassava, and rice, generating insights into determinants of efficiency variation [9].

For biofortified crops, efficiency analysis is particularly valuable as it reveals whether adoption translates into higher productivity or whether inefficiencies undermine potential benefits [10]. For example, if biofortified maize adopters exhibit low efficiency due to poor input use or weak extension support, then the nutritional promise of biofortification may remain unrealized. Conversely, high efficiency among adopters would signal both agronomic and nutritional success [11].

The conceptual framework guiding this article integrates adoption theories with efficiency analysis, recognizing the dual role of farmer decisions and management performance in shaping outcomes.

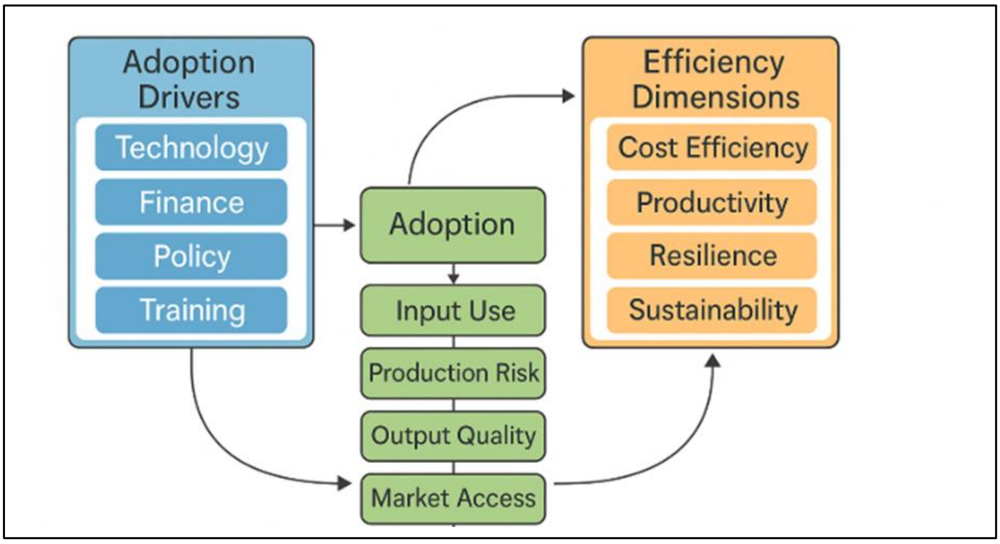

Figure 1 Conceptual framework of adoption and efficiency linkages

This framework underscores that adoption is not sufficient; efficiency determines the extent to which biofortified crops can improve food security and nutrition resilience in North-Central Nigeria [8].

3. Study context: North-central Nigeria

3.1. Socioeconomic Profile of Farmers

The socioeconomic profile of smallholder farmers in North-Central Nigeria is diverse but shaped by structural similarities in landholding, demographic composition, and income sources. Most households are headed by middle-aged farmers, often between 35 and 55 years, reflecting a generational dominance of agricultural participation [13]. Younger farmers, while present, frequently combine farming with other forms of employment, highlighting the role of agriculture as both a primary and supplementary income stream [16].

Landholding patterns are typically small and fragmented. The average farm size ranges from 1 to 3 hectares, with many farmers cultivating plots dispersed across different locations. This fragmentation, coupled with insecure land tenure, constrains long-term investment in soil fertility or irrigation infrastructure [12]. Women farmers often manage smaller plots within family holdings, concentrating on crops that serve dual roles of household consumption and local market sales. This gendered distribution of land access reflects broader social inequalities in agricultural productivity [15].

Income sources are equally heterogeneous. In addition to crop farming, households derive income from livestock rearing, petty trading, artisanal work, and seasonal migration. Such diversification is a coping mechanism in response to fluctuating agricultural yields and market uncertainties [14]. Remittances from family members in urban centers also contribute to income stability, though their role varies across communities.

Educational attainment among farmers tends to be modest, with many having only primary or secondary schooling. This influences awareness and adoption of agricultural innovations, as literacy levels affect the ability to interpret extension messages, input labels, and technical advice [17]. Taken together, the socioeconomic profile demonstrates the vulnerabilities and opportunities that shape the adoption and efficiency of biofortified crops in the region.

3.2. Agricultural Systems and Crop Choices

North-Central Nigeria is characterized by mixed crop–livestock systems, where staple cereals and legumes dominate farming portfolios. Maize, sorghum, millet, and yam form the backbone of household diets, supplemented by cowpea, groundnut, and cassava [16]. These crops provide subsistence for farmers but are also marketed in local and regional trade networks, ensuring a steady flow of both cash and food security benefits.

Food security challenges are widespread. Rain-fed agriculture predominates, leaving farmers highly vulnerable to climate variability, including late rains, prolonged dry spells, and soil fertility depletion [14]. Seasonal hunger periods remain common, particularly among low-income households that struggle to bridge consumption gaps between harvests. Post-harvest losses, estimated to reach as high as 30 percent for perishable crops, further constrain availability and incomes [12].

Crop choices are guided not only by dietary needs but also by cultural practices and market opportunities. Yam, for example, carries symbolic and ceremonial value, while maize has become increasingly central to urban consumption. Legumes such as cowpea and groundnut are valued for both food and soil-enriching properties. Despite this diversity, nutritional outcomes remain constrained by reliance on staple cereals low in micronutrients [13].

The introduction of biofortified crops seeks to address these nutritional limitations while aligning with existing systems. Vitamin A maize, orange-fleshed sweet potatoes, and iron beans complement staple diets, offering enhanced nutritional profiles without requiring radical changes in consumption habits [15]. Yet the extent to which these crops displace or integrate with existing crop portfolios depends on perceptions of yield, marketability, and labor requirements [17]. This dynamic situates biofortification within broader questions of food security, resilience, and cultural adaptation in North-Central Nigeria.

3.3. Extension Services and Market Access

Institutional support through extension services plays a decisive role in shaping agricultural innovation uptake in North-Central Nigeria. Public extension services are understaffed and underfunded, limiting their ability to reach remote communities consistently [13]. Many farmers report infrequent contact with extension agents, often only during the distribution of subsidized inputs or donor-supported programs [14]. Consequently, awareness of biofortified crops is uneven, with better-connected farmers more likely to receive training and information.

Cooperatives and farmer-based organizations have emerged as important alternatives, facilitating collective access to seeds, fertilizers, and markets [16]. Participation in cooperatives increases bargaining power and reduces transaction costs, enabling smallholders to better integrate into value chains. These organizations also serve as conduits for biofortification initiatives, amplifying outreach and training efforts.

Market access remains constrained by poor road infrastructure, high transport costs, and limited storage facilities [12]. Farmers located near urban centers are better positioned to sell surpluses, while remote communities face difficulties in connecting to profitable markets. Such spatial disparities directly affect incentives for adopting new crops. Geographic considerations also shape intervention design.

Figure 2 Map of North-Central Nigeria highlighting study areas [12]

Study areas selected for this research illustrate variations in extension coverage, market connectivity, and institutional presence. These contrasts provide a useful lens for understanding how structural differences mediate both adoption and efficiency outcomes of biofortified crops [17].

3.4. Biofortified Crop Interventions

Several biofortified crops have been introduced in North-Central Nigeria, spearheaded by collaborations among international research institutions, government agencies, and local NGOs [15]. The most prominent interventions include vitamin A maize, orange-fleshed sweet potato (OFSP), and iron-biofortified beans. These crops were strategically selected due to their compatibility with local diets and their potential to address widespread micronutrient deficiencies [14].

Vitamin A maize has gained traction as a substitute for conventional white maize, offering both agronomic competitiveness and nutritional value [13]. OFSP, though initially limited by cultural unfamiliarity with orange-colored varieties, has gradually gained acceptance through awareness campaigns and demonstration plots. Iron beans, still at an earlier stage of dissemination, target anemia reduction and diversify household diets.

The success of these interventions depends not only on seed availability but also on farmer perceptions of yield, taste, and marketability [12]. Adoption is further influenced by institutional support, such as input subsidies and extension training. However, gaps remain in ensuring equitable access to improved seeds, particularly for marginalized groups such as women and resource-poor households [17].

Table 1 Characteristics of Sampled Farmers and Households

Characteristic	Adopters of Biofortified Crops (%)	Non-Adopters (%)	Overall Sample (%)
Household Head (Gender)	Male: 71.5 Female: 28.5	Male: 79.0 Female: 21.0	Male: 75.2 Female: 24.8
Average Age of Household Head	44.8 years	47.2 years	46.0 years
Education Level	No formal: 15.6 Primary: 32.1 Secondary+: 52.3	No formal: 22.4 Primary: 38.7 Secondary+: 38.9	No formal: 19.0 Primary: 35.2 Secondary+: 45.8
Household Size	≤5 members: 36.5 >5 members: 63.5	≤5 members: 41.2 >5 members: 58.8	≤5 members: 38.9 >5 members: 61.1
Landholding Size	<2 ha: 42.8 ≥2 ha: 57.2	<2 ha: 56.1 ≥2 ha: 43.9	<2 ha: 49.4 ≥2 ha: 50.6
Income Sources	Agriculture only: 68.3 Diversified: 31.7	Agriculture only: 74.5 Diversified: 25.5	Agriculture only: 71.2 Diversified: 28.8
Extension Contact (past year)	Yes: 61.2 No: 38.8	Yes: 44.6 No: 55.4	Yes: 52.9 No: 47.1
Cooperative Membership	Yes: 48.9 No: 51.1	Yes: 29.7 No: 70.3	Yes: 39.3 No: 60.7

This table summarizes demographic, socioeconomic, and farm-level attributes of surveyed households, situating biofortified crop interventions within their lived realities. Linking these characteristics to adoption dynamics allows for a deeper understanding of how biofortification intersects with technical efficiency and food security outcomes [16].

4. Determinants of adoption

4.1. Household Characteristics

Household characteristics significantly shape the likelihood of adopting biofortified crops in North-Central Nigeria. Age is a critical factor, as younger farmers are generally more open to experimentation and new technologies, while older farmers often rely on long-established practices [18]. Education levels influence awareness and the ability to interpret technical advice, particularly regarding the nutritional benefits of biofortification [22]. Households with higher literacy rates are better equipped to engage with extension materials, input guides, and demonstration activities.

Gender also plays a decisive role. Female-headed households, though active in biofortified crop cultivation, often face structural disadvantages in accessing land, credit, and extension support [20]. Nevertheless, women's role in household food preparation positions them as critical agents of adoption, since their influence extends directly to dietary choices [16]. Household size can either enhance or hinder adoption. Larger households provide labor for land preparation and harvesting but may also increase consumption demands, leaving less surplus for sale [19].

Decision-making dynamics within households also matter. In families where agricultural decisions are shared between spouses, biofortified crops tend to be adopted more readily due to joint recognition of their nutritional and economic benefits [21]. Conversely, male-dominated decision structures can limit adoption if nutritional concerns are undervalued compared to cash crop priorities. Collectively, household characteristics provide a nuanced understanding of adoption heterogeneity, demonstrating that demographic and social factors must be accounted for when designing effective dissemination strategies for biofortified crops [23].

4.2. Farm Characteristics

Farm-level factors also influence adoption decisions. Land size determines the extent to which farmers can allocate space to experimental or less familiar varieties such as vitamin A maize or orange-fleshed sweet potato [17]. Larger landholders tend to adopt more quickly because they can diversify plots and test innovations without risking overall food security [19]. By contrast, resource-constrained smallholders must prioritize short-term yield reliability, reducing willingness to shift from conventional varieties [21].

Input use, particularly fertilizers and improved seeds, correlates strongly with biofortified crop adoption [22]. Farmers accustomed to using hybrid seeds or agrochemicals display higher readiness to integrate biofortified options, reflecting both their openness to innovation and the compatibility of new technologies with existing practices [20]. Access to irrigation also supports adoption by mitigating seasonal risks associated with perishable crops such as orange-fleshed sweet potato [16].

Credit availability is another decisive determinant. Households with access to microfinance institutions or cooperative loans are more likely to purchase biofortified seeds, fertilizers, and labor inputs [23]. Conversely, limited access to credit constrains adoption, particularly among women and younger farmers. Informal borrowing networks partially fill this gap, though they are inconsistent and often inadequate for significant investment.

Overall, farm characteristics highlight the structural inequities shaping adoption outcomes. Larger, better-capitalized farms have the means to integrate innovations more rapidly, while smaller farmers face barriers that perpetuate productivity and nutritional disparities. Addressing these gaps requires policies that ensure equitable access to land, inputs, and credit facilities [18].

4.3. Institutional Factors

Institutional support is central to biofortified crop adoption. Extension services are the most direct channel of dissemination, though coverage remains uneven in North-Central Nigeria [16]. Farmers with regular extension contact are significantly more likely to adopt biofortified crops, as they gain access to both technical training and demonstrations on agronomic practices [20]. The frequency of visits often determines the depth of understanding, with sporadic interactions resulting in partial or incorrect adoption [21].

Training programs, organized through NGOs and government projects, further enhance adoption rates. Practical sessions, particularly those involving demonstration plots, enable farmers to observe yield performance and taste qualities of biofortified crops firsthand [17]. These experiential methods are more persuasive than theoretical explanations, especially for low-literacy farmers. Farmer field schools and participatory learning activities strengthen peer-to-peer diffusion, extending the reach of training initiatives [22].

Membership in cooperatives or farmer associations amplifies institutional influence. Cooperatives provide collective bargaining for inputs, facilitate group-based training, and create trusted platforms for introducing biofortified varieties [23]. They also reduce transaction costs by pooling risks and increasing economies of scale in seed procurement and distribution [19].

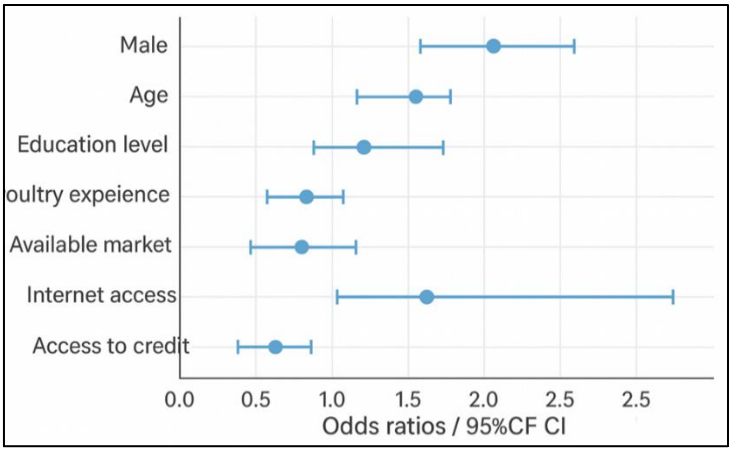

Figure 3 Logistic regression result of adoption terminates

This figure illustrates the relative strength of institutional variables compared to household and farm-level factors, highlighting the decisive role of extension frequency, training access, and cooperative membership. Such evidence reinforces the argument that adoption is not merely an individual decision but a socially and institutionally mediated process [18].

4.4. Market and Policy Environment

The broader market and policy context significantly influences adoption. Market incentives, such as premium prices for biofortified crops, encourage adoption by linking nutritional value to tangible financial benefits [20]. For example, vitamin A maize commands slightly higher prices in urban markets where awareness campaigns have emphasized its health advantages [21]. Farmers aware of such price differentials are more motivated to integrate biofortified crops into their production systems [16].

Government subsidies and input support programs also play a critical role. Seed distribution schemes, often tied to seasonal input subsidies, reduce financial risks for farmers trialing biofortified crops [23]. However, inconsistencies in policy implementation such as delays in input delivery or politicized distribution limit their effectiveness [22]. Stable and transparent policies are needed to build trust and ensure consistent farmer participation.

Awareness campaigns, conducted via radio, community meetings, and school feeding programs, increase consumer demand and thereby strengthen incentives for farmers [19]. These campaigns not only highlight nutritional benefits but also reduce misconceptions about biofortified crops, such as concerns over taste or cooking properties [18].

Regional trade dynamics also affect adoption. Farmers near urban centers or cross-border markets adopt biofortified crops more readily due to stronger market signals [17]. Conversely, remote farmers face lower demand visibility, which weakens adoption incentives. Overall, the market and policy environment underscores the importance of aligning nutritional goals with economic realities, ensuring that adoption is both desirable and feasible across diverse farming systems [20].

5. Technical efficiency analysis

5.1. Methodology: Stochastic Frontier or DEA

The assessment of technical efficiency among smallholder farmers adopting biofortified crops in North-Central Nigeria was conducted using both stochastic frontier analysis (SFA) and data envelopment analysis (DEA). The stochastic frontier framework allows for the estimation of efficiency by distinguishing between random shocks and inefficiency, a valuable feature in agricultural systems where weather, pests, and market fluctuations play significant roles [22]. The production function was specified in a Cobb–Douglas form, capturing the relationship between outputs and key inputs such as land, labor, seed, and fertilizer [26].

DEA complements this by applying a non-parametric approach to construct an efficiency frontier without imposing assumptions on functional form [24]. It uses linear programming to benchmark farmers against the best-performing peers, thereby providing a flexible measure of relative efficiency. Both methods assume rational farmer behavior but differ in sensitivity to data errors. While DEA is deterministic and attributes all deviations from the frontier to inefficiency, SFA separates inefficiency from statistical noise [27].

Together, these approaches provide a robust assessment framework, triangulating results and reducing biases associated with any single model. This dual-method approach enhances the reliability of findings on how adoption of biofortified crops translates into efficiency gains in local farming systems [25].

5.2. Efficiency Scores among Adopters vs. Non-Adopters

Comparative analysis of efficiency scores reveals clear differences between adopters and non-adopters of biofortified crops. Using SFA estimates, adopters achieved an average efficiency score of 0.78 compared to 0.62 for non-adopters, suggesting that biofortification adoption enhances productive performance [23]. DEA results further confirmed this pattern, with adopters demonstrating a higher proportion of farmers clustered near the efficient frontier [28].

These differences are particularly significant for smaller farms, where efficiency improvements represent critical pathways to food security and income stability [24]. Adopters benefited from improved seed quality and better agronomic practices introduced alongside biofortified varieties, such as precise planting densities and fertilizer application guidelines [26]. By contrast, non-adopters often relied on traditional seed-saving practices that reduced productivity and perpetuated inefficiency.

The distribution of efficiency scores also revealed a narrowing of performance gaps within adopter groups. Adopters showed less variation in efficiency, indicating that biofortified crop interventions promote more standardized and consistent practices [25]. Conversely, non-adopters displayed wider variability, with some farmers operating well below potential yields due to limited access to extension services or inputs [22].

Overall, the results highlight adoption as a catalyst for improved efficiency outcomes. While other structural constraints persist, the evidence demonstrates that biofortified crop adoption contributes meaningfully to narrowing yield gaps and strengthening the resilience of smallholder farming systems [27].

5.3. Key Drivers of Efficiency

Determinants of technical efficiency highlight the role of both household and institutional factors. Land size emerged as a significant driver, with larger farms achieving higher efficiency scores due to economies of scale in input use [24]. Experience also mattered, as farmers with more years in cultivation displayed stronger resource allocation skills and better timing of operations [26]. Education and training influenced efficiency by enhancing farmers' capacity to understand and apply improved agronomic recommendations [23].

Access to inputs, including fertilizer and improved seed, remained central. Farmers using biofortified varieties alongside modern inputs recorded consistently higher scores [25]. Extension services reinforced this effect by ensuring accurate adoption of recommended practices [28]. Participation in cooperatives provided collective bargaining power for input procurement, further supporting efficient outcomes [22].

Table 2 Technical Efficiency Scores and Determinants

Variable	Adopters (Mean/%)	Non-Adopters (Mean/%)	Effect on Efficiency
Average Technical Efficiency (SFA)	0.78	0.62	Higher among adopters; biofortified inputs improved productivity
Average Technical Efficiency (DEA)	0.81	0.65	Consistent with SFA, adopters clustered closer to frontier
Landholding Size (≥2 ha)	57.2%	43.9%	Larger farms improved efficiency via economies of scale
Education (Secondary or higher)	52.3%	38.9%	Better education enhanced adoption of efficiency practices
Extension Contact (last 12 months)	61.2%	44.6%	Access to training improved agronomic practices

Cooperative Membership	48.9%	29.7%	Collective input access reduced inefficiency
Access to Credit	42.5%	24.3%	Enabled purchase of improved inputs and timely operations
Experience (≥10 years)	64.1%	58.7%	More experienced farmers allocated resources more efficiently

Table 2 synthesizes these findings, presenting comparative efficiency scores between adopters and non-adopters, while also mapping determinants such as landholding, education, and input access. The evidence underscores that adoption alone is not sufficient supportive structures such as training, credit, and input availability are essential to fully unlock efficiency gains [27].

5.4. Implications for Productivity

The analysis of efficiency outcomes underscores significant implications for productivity growth in North-Central Nigeria. Efficiency gaps between adopters and non-adopters point to substantial room for yield improvements if adoption is broadened and supported through institutional frameworks [23]. Closing these gaps could contribute to both food security and poverty reduction by raising household-level production and reducing reliance on costly imports [25].

Furthermore, the findings suggest that biofortified crop adoption is not only nutrition-sensitive but also efficiency-enhancing [24]. Farmers who integrate improved technologies, supported by extension and cooperative networks, can achieve near-frontier performance levels. Conversely, persistent inefficiencies among non-adopters signal the importance of targeted interventions to reduce barriers to entry, particularly among resource-constrained farmers [26].

Ultimately, fostering broad adoption of biofortified crops while strengthening institutional support structures can transform productivity landscapes in the region, contributing to sustainable agricultural development and resilience against nutritional and economic vulnerabilities [28].

6. Discussion

6.1. Key Findings on Adoption

The analysis of adoption dynamics in North-Central Nigeria reveals that socioeconomic and institutional enablers were central to shaping uptake of biofortified crops. Education, household size, and access to extension services were consistently significant, highlighting the importance of knowledge dissemination and community engagement [27]. Farmers with higher educational attainment demonstrated greater willingness to experiment with biofortified varieties, reflecting broader evidence that human capital strengthens receptivity to agricultural innovation [32].

Institutional access emerged as another determinant. Membership in cooperatives facilitated collective learning and improved bargaining power in accessing inputs. These groups often acted as conduits for distributing vitamin A maize or orange-fleshed sweet potato vines, thereby increasing visibility and confidence in biofortified crops [30]. In contrast, farmers operating outside cooperative structures were more reliant on informal seed systems and faced higher barriers to adoption [28].

Demographic characteristics also influenced adoption patterns. Youth and women were relatively more engaged in biofortified crop trials, a finding consistent with the positioning of biofortification as a nutrition-sensitive technology that resonates with household food security concerns [29]. Women, in particular, prioritized crops such as orange-fleshed sweet potatoes due to their shorter maturity periods and direct relevance to household nutrition [31].

Ultimately, adoption was not driven by nutrition benefits alone but by a mix of agronomic performance, market access, and institutional support [33]. Farmers who perceived biofortified crops as higher yielding and marketable were significantly more likely to adopt, reinforcing the need for an integrated lens that situates biofortification within broader livelihood and resilience strategies [34]. These findings highlight adoption as a socially and institutionally embedded process rather than a purely individual decision [35].

6.2. Key Findings on Efficiency

The efficiency analysis underscored that biofortified crop adoption and technical efficiency are closely linked. Adopters consistently recorded higher efficiency scores than non-adopters, suggesting that improved inputs and associated training translated into better resource utilization [30]. This nexus demonstrates that adoption of biofortified crops is not merely a nutritional intervention but also a productivity-enhancing strategy [27].

Households that adopted vitamin A maize or iron beans benefited from structured extension advice that promoted optimal planting densities, fertilizer use, and pest control [32]. These agronomic practices contributed to reduced inefficiency by standardizing production processes and narrowing performance disparities among farmers [28]. Conversely, non-adopters continued to rely on traditional inputs and practices, often leading to yield gaps and vulnerability to climatic or pest shocks [33].

Efficiency gains were not uniform, however. Access to credit, education, and cooperative membership continued to mediate performance outcomes. Farmers with better institutional support maximized the benefits of biofortified crops, while those without such access still lagged behind despite adoption [34]. This underscores the need to pair technology dissemination with structural support to ensure inclusivity in efficiency gains [31].

The findings thus position adoption as a driver of efficiency but also point to persistent inequalities in resource access. Bridging these disparities remains a priority if biofortification is to serve as both a nutrition-sensitive and productivity-oriented agricultural strategy for smallholders in Nigeria [29].

6.3. Policy Implications

The empirical results generate critical lessons for Nigeria's agricultural and nutrition strategies. First, the dual benefits of biofortification nutrition and efficiency reinforce the importance of mainstreaming biofortified crops within national agricultural extension frameworks [32]. Extension officers must be trained not only to promote nutritional advantages but also to deliver agronomic best practices that sustain efficiency gains [27].

Second, policies must strengthen seed systems to ensure that biofortified varieties are accessible, affordable, and widely distributed. Weaknesses in seed availability were a recurring barrier across study areas, often discouraging adoption even among farmers aware of the nutritional benefits [35]. Expanding certified seed networks and linking them with cooperatives can improve both availability and trust [28].

Third, gender-sensitive policies are vital. Women's central role in adopting nutrition-focused crops requires targeted interventions that reduce barriers to land access, credit, and extension participation [30]. Youth engagement also deserves focus, as younger farmers show higher openness to experimentation with biofortification [33].

Finally, at the strategic level, biofortification should be integrated into Nigeria's food security and nutrition action plans. Doing so would align agricultural policies with health objectives and strengthen cross-sectoral collaboration [29]. This integration is particularly urgent in light of the persistent burden of micronutrient deficiencies and rising food insecurity.

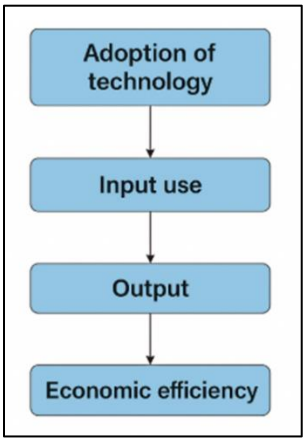

Figure 4 Adoption–efficiency pathways for smallholder farmers

Figure 4 synthesizes these policy implications by illustrating how adoption enablers, efficiency determinants, and structural supports interact to influence household-level outcomes, emphasizing the systemic nature of biofortification's impact [34].

6.4. Comparative Perspectives

Situating these findings within the global biofortification literature reveals both convergence and divergence. The Nigerian experience echoes patterns observed in East Africa, where adoption of orange-fleshed sweet potatoes was shaped by institutional support and women's involvement [31]. Similarly, studies in South Asia on iron-biofortified beans and zinc rice confirm the centrality of extension and seed access in driving adoption [27].

However, Nigeria's context is distinguished by structural inefficiencies in input markets and infrastructural challenges that exacerbate adoption barriers [35]. Unlike Latin America, where state-led programs anchored biofortification within public procurement schemes, Nigeria's reliance on donor-driven interventions has limited scale and sustainability [28].

The efficiency dimension also provides a unique contribution. While global studies often focus on nutritional outcomes, this analysis demonstrates that biofortified crops simultaneously drive technical efficiency, thereby bridging nutrition and productivity agendas [32]. This dual framing strengthens the argument for integrating biofortification into national agricultural policies as a holistic solution rather than a niche intervention [29].

In sum, Nigeria's experience adds to global evidence by highlighting how adoption and efficiency pathways intersect under conditions of structural vulnerability. It underscores the necessity of designing interventions that are not only nutrition-sensitive but also efficiency-oriented [33].

7. Conclusion

7.1. Summary of Findings

This study examined the adoption and technical efficiency of biofortified crops among smallholder farmers in North-Central Nigeria, focusing on both socioeconomic and institutional enablers. The evidence shows that education, cooperative membership, and access to extension services were the strongest determinants of adoption. Demographic factors such as youth and women's engagement also shaped uptake, reflecting the nutrition-sensitive appeal of crops like vitamin A maize and orange-fleshed sweet potatoes.

Beyond adoption, technical efficiency analysis revealed that adopters consistently outperformed non-adopters, with higher scores across both stochastic frontier and data envelopment frameworks. These gains were attributed to improved seed quality, structured extension support, and access to key inputs. However, efficiency was not universal; disparities persisted where farmers lacked credit, training, or cooperative linkages.

Taken together, the findings highlight the dual role of biofortified crops: they are not only nutritional interventions but also pathways to improved productivity. Adoption fosters efficiency, but institutional and market supports are essential to maximize benefits. Without these structures, gaps in performance remain, leaving segments of smallholders unable to capture the potential of biofortification. Thus, the study underscores biofortification as both a nutrition and livelihood strategy, contingent on effective policy and institutional frameworks.

7.2. Recommendations

To scale adoption and maximize efficiency gains, several strategic actions are recommended. At the policy level, biofortified crops should be mainstreamed into Nigeria's agricultural and nutrition strategies. Government investment in certified seed systems, combined with gender- and youth-focused programs, will be critical to enhancing accessibility and inclusivity. Integrating biofortification into national food security plans would also align agriculture with health priorities, strengthening cross-sector collaboration.

Institutionally, extension services need to be retooled to emphasize both nutritional and agronomic benefits. Training officers on efficiency-enhancing practices such as optimal planting densities and input application will ensure that farmers not only adopt but also use biofortified crops effectively. Cooperatives should be empowered as distribution and learning hubs, reducing barriers related to seed availability, knowledge transfer, and market access.

At the farmer level, capacity building through localized demonstrations, farmer field schools, and peer learning platforms can reduce skepticism and foster adoption. Access to microcredit tailored to biofortified crop production should also be expanded, enabling smallholders to overcome upfront costs associated with improved inputs. Collectively, these actions would create an enabling environment where biofortification contributes simultaneously to nutrition security, efficiency, and resilience in rural households.

7.3. Final Reflections

The future of biofortification in Nigeria lies in its ability to move beyond pilot projects toward systemic integration. This requires not only strengthening adoption but also ensuring efficiency gains are equitably distributed across farming communities. With the right mix of policy support, institutional capacity, and farmer engagement, biofortified crops can serve as a bridge between nutrition goals and productivity growth. Ultimately, the resilience of smallholder farming systems depends on innovations that address both health and livelihoods. Biofortification, when scaled inclusively, holds the promise of transforming Nigeria's food landscape into one that is more secure, equitable, and sustainable.

References

[1] Igbaifua WE, Adeniyi OR, Omolehin RA. Comparative Analysis of Technical, Allocative and Economic Efficiencies of Vitamin A Cassava Farmers with Other Improved Cassava Farmers in Oyo State, Nigeria. Journal of Research in Agriculture and Animal Science. 2021;8(11):60-73.

[2] Okwuonu IC, Narayanan NN, Egesi CN, Taylor NJ. Opportunities and challenges for biofortification of cassava to address iron and zinc deficiency in Nigeria. Global Food Security. 2021 Mar 1;28:100478.

[3] Oparinde A, Abdoulaye T, Manyong VM, Birol E, Asare-Marfo D, Kulakow P, Ilona P. A technical review of modern cassava technology adoption in Nigeria (1985-2013): Trends, challenges, and opportunities.

[4] Otekunrin OA, Otekunrin OA, Sawicka B, Pszczółkowski P. Assessing food insecurity and its drivers among smallholder farming households in rural Oyo State, Nigeria: the HFIAS approach. Agriculture. 2021 Nov 25;11(12):1189.

[5] Yusuf OJ, Opeyemi M. Market participation and food security status of bio-fortified cassava processors in South Western Nigeria. International Journal. 2020;7(3):174-84.

[6] Oparinde A, Abdoulaye T, Mignouna DB, Bamire AS. Will farmers intend to cultivate Provitamin A genetically modified (GM) cassava in Nigeria? Evidence from ak-means segmentation analysis of beliefs and attitudes. PLoS One. 2017 Jul 11;12(7):e0179427.

[7] Oyawole FP, Dipeolu AO, Shittu AM, Obayelu AE, Fabunmi TO. Adoption of agricultural practices with climate smart agriculture potentials and food security among farm households in northern Nigeria. Open Agriculture. 2020 Nov 18;5(1):751-60.

[8] Onyemma JO, Tertsea KM, Ogbonna NK, Chimela NS. Level of adoption o f improved cassava technologies in Benue State. J. Appl. Life Sci. Int. 2019;21(2):1-3.

[9] Udemezue JC, Eluagu CJ, Azodo NT, Odia FN, Onwuneme NA. Economic Benefits and Adoption of Orange-Fleshed Sweetpotato Production Enterprise among Farmers. Agric Ext J. 2021;5:1-8.

[10] Ndjouenkeu R, Ngoualem Kegah F, Teeken B, Okoye B, Madu T, Olaosebikan OD, Chijioke U, Bello A, Oluwaseun Osunbade A, Owoade D, Takam-Tchuente NH. From cassava to gari: mapping of quality characteristics and end-user preferences in Cameroon and Nigeria. International Journal of Food Science and Technology. 2021 Mar;56(3):1223-38.

[11] Guiné RP, Correia P, Leal M, Rumbak I, Barić IC, Komes D, Satalić Z, Sarić MM, Tarcea M, Fazakas Z, Jovanoska D. Cluster analysis to the factors related to information about food fibers: A multinational study. Open agriculture. 2020 Oct 6;5(1):593-606.

[12] Farré G, Gómez-Galera S, Naqvi S, Bai C, Sanahuja G, Yuan D, Zorrilla-López U, Codony L, Rojas E, Fibla M, Twyman R. Encyclopedia of sustainability science and technology. Springer New York, New York, NY, NY; 2012.

[13] Carolan M. The sociology of food and agriculture. Routledge; 2016 Feb 12.

[14] Nkonya E, Bashaasha B, Kato E, Bagamba F, Danet M. Impact of creative capacity building of local innovators and communities on income, welfare and attitudes in Uganda. 3ie Impact Evaluation Report 124. New Delhi: International Initiative for Impact Evaluation (3ie). 2020 Jul.

[15] Marenya PP. A Background Study for the CGIAR Social Sciences Stripe Review Commissioned by the CGIAR Science Council Phase 1 (Task 1–2 and Output 1).

[16] Costich DE, Smith JS, Gardner C, Akinwale RO, Fakorede MA, Bada-Apraku B, Carena MJ, Wu Y, Messing J, Williams WP, Warburton M. Achieving sustainable cultivation of maize Volume 1: From improved varieties to local applications. Burleigh Dodds Science Publishing; 2017 Jun 9.

[17] Nagothu US. Agricultural Development and Sustainable Intensification. 2018.

[18] Schnurr MA. GMOs and poverty: yield gaps, differentiated impacts and the search for alternative questions. Canadian Journal of Development Studies/Revue canadienne d'études du développement. 2017 Jan 2;38(1):149-57.

[19] Ahmadi Dehrashid A, Bijani M, Valizadeh N, Ahmadi Dehrashid H, Nasrollahizadeh B, Mohammadi A. Food security assessment in rural areas: evidence from Iran. Agriculture & food security. 2021 Jun 18;10(1):17.

[20] Nyagumbo I, Tesfai M, Nagothu US, Setimela P, Karanja JK, Mutenje M, Madembo C. Sustainable intensification and maize value chain improvements in sub-Saharan Africa. InAgricultural Development and Sustainable Intensification 2018 May 11 (pp. 52-80). Routledge.

[21] Njoku DN, Mbah EU. Assessment of yield components of some cassava (Manihot esculenta Crantz) genotypes using multivariate analysis such as path coefficients. Open Agriculture. 2020 Sep 8;5(1):516-28.

[22] Wanga MA, Kumar AA, Kangueehi GN, Shimelis H, Horn LN, Sarsu F, Andowa JF. Breeding sorghum using induced mutations: Future prospect for Namibia. American Journal of Plant Sciences. 2018 Dec 5;9(13):2696-707.

[23] Onumah G, Dipeolu A, Fetuga G. Report on sweetpotato value chain study: Exploring opportunities to promote greater exploitation of the benefits of sweetpotato in representative states of Nigeria. Unpublished report. 2012 May.

[24] Ishikawa H, Matsumoto R. Diversified approaches to evaluate wide genetic resources of cowpea for enhancing new variety development for West Africa and its social implementation by cowpea research program of IITA. Japan Agricultural Research Quarterly: JARQ. 2021 Dec 1;55(Special):443-62.

[25] Kuku-Shittu O, Onabanjo O, Fadare O, Oyeyemi M. Child malnutrition in Nigeria: evidence from Kwara State. Intl Food Policy Res Inst; 2016 Aug 10.

[26] Omache NR. Factors influencing agricultural productivity in Kenya: A case of Nyathuna ward in Kabete Sub-County, Kiambu County. Unpublished Masters Dissertation, University of Nairobi Kenya. 2016.

[27] Rahaman MS, Haque S, Sarkar MA, Rahman MC, Reza MS, Islam MA, Siddique MA. A cost efficiency analysis of boro rice production in Dinajpur district of Bangladesh. Fundamental and Applied Agriculture. 2021;6(1):67-77.

[28] Opaluwah A. TAAT News: A quarterly publication of technologies for African Agricultural Transformation (TAAT) Program. April–June 2019. Vol 2. Gates Open Res. 2021 Aug 23;5(133):133.

[29] Bello SD, Salin KR, Kuwornu JK. Willingness to adopt aquaculture as an alternative livelihood option-a case study of the fishers and livestock farmers of Adamawa State, Nigeria. International Journal of Value Chain Management. 2021;12(1):28-44.

[30] Adeleke EA, Ahungwa GT, Yusuf I. Health implication of industrial pollution and farm household's willingness to relocate from cement factories in Ogun State Nigeria. Journal of Agriculture, Food Security and Sustainable Environment. 2018;1(1):1-2.

[31] Tiamiyu MA, Bankole AS, Agbonlahor RO. Catalytic mechanisms for promoting ICT investment and use in cassava value chains in south-western Nigeria. Information Development. 2012 May;28(2):132-48.

[32] Chianu JN, Nkonya EM, Mairura FS, Chianu JN, Akinnifesi FK. Biological nitrogen fixation and socioeconomic factors for legume production in Sub-Saharan Africa. InSustainable Agriculture Volume 2 2011 Jan 7 (pp. 309-329). Dordrecht: Springer Netherlands.

[33] Olawuyi SO, Mushunje A. Impact of Output Market Participation on Cassava-based Farming Households' Welfare: Evidence from Oyo State, Nigeria. Journal of Economic & Management Perspectives. 2018 Jun 1;12(2):575-88.

[34] Goredema-Matongera N, Ndhlela T, Magorokosho C, Kamutando CN, van Biljon A, Labuschagne M. Multinutrient biofortification of maize (Zea mays L.) in Africa: current status, opportunities and limitations. Nutrients. 2021 Mar 23;13(3):1039.

[35] Juma C. The new harvest: agricultural innovation in Africa. Oxford University Press; 2015 Aug 3.