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RESEARCH ARTICLE

Agrivoltaics Potentials for Food Processing and Water Supply in Rural Electrification-deficient Areas: A Case Study of Anambra Agricultural Zones, Nigeria

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Abstract

Reliable electricity remains a significant barrier to agricultural productivity in rural Nigeria. This case study investigated the potential of agrivoltaic systems, combining solar energy generation with crop production, to address food processing and water supply challenges in the Anambra State Agricultural Zones. Drawing on the Technology Acceptance Model (TAM), a cross-sectional survey was administered to 845 respondents, of whom 840 returned valid questionnaires, food processors, and water facility operators across 16 communities using probability-proportional-to-size sampling (design effect = 2.0). Descriptive statistics and ordinal logistic regression were used to assess perceptions and associations. Results showed strong agreement that agrivoltaic systems could reduce post-harvest losses (mean = 4.2) and improve water pumping consistency (mean = 4.5). Ordinal logistic regression revealed that willingness to adopt agricultural systems was significantly associated with higher perceived improvements in food processing (OR = 1.42, $p < 0.01$) and water supply (OR = 1.53, $p < 0.01$). Major barriers included high upfront costs, land tenure insecurity (42% of respondents do not hold family-owned land titles, relying instead on communal, rental, or informal arrangements), and concerns about panel damage from heavy rains and winds (mean = 4.18) as well as battery replacement costs (mean = 2.34). A simplified levelized cost of energy (LCOE) comparison found solar agricultural systems (₦80/kWh) substantially cheaper than diesel generators (₦736/kWh). All regression findings are associational, not causal, due to potential reverse causality and omitted variable bias. As a case study of Anambra's humid tropical zone, findings are not directly generalizable to semi-arid or Sahelian regions. Recommendations include government-subsidized pilot projects, community-based land tenure agreements, and local technical training.

Keywords: agrivoltaics, rural electrification, food processing, water supply, Anambra Agricultural Zones.

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1 Introduction

For many years, rural communities across sub-Saharan Africa have faced a constant struggle with inadequate energy supply, a challenge that continues to weaken agricultural value chains. In Nigeria, this situation is particularly striking [1]. Despite its status as a leading oil-producing nation, electricity use per person remains among the lowest in the world, with estimates placing annual consumption at about 140–144 kWh per capita, compared to the global average of 3,128 kWh [2–4]. In practice, electricity use at the household level is far from stable. There are frequent outages and limited grid access, especially in rural areas where many households depend heavily on small oil generators to meet their daily energy needs. Across the agricultural zones of Anambra State, an area well known for producing yam, rice, cassava, and vegetables [5], reliable electricity is largely out of reach.

In many communities, power supply is either completely unavailable or comes on for just a few unpredictable hours each week. Farmers and small-scale food processors have adapted by relying on diesel generators, kerosene, or open fires. But these alternatives are expensive, unhealthy, and environmentally damaging [6, 7]. The situation creates a cruel irony: rich agricultural lands produce harvests that then rot because there is no power to process, cool, or pump water for irrigation. In the rural setting, food processing is mostly done by manual techniques [8, 9] or through small local mills that rely on generators, which don't always have fuel available. Women, who take care of most post-harvest tasks, often spend long hours pounding, drying, or smoking the crops. Because there's no reliable cold storage, tomatoes, leafy vegetables, and other fresh foods often begin to spoil in as little as two days. That loss isn't just about food or money; it also means all the effort, water, and fertilizer used to grow them goes to waste. Access to clean water is also a major problem. In many rural areas, boreholes depend on electric pumps that only work when there's power or when families can afford to run a generator. In the dry season, the situation gets even worse as water levels drop and pumping requires more depth, and more fuel. As a result, people often fall back on unsafe sources like streams or shallow hand-dug wells [10]. This increases the risk of waterborne illnesses, which in turn reduces the number of people able to work on farms [11, 12].

Agrivoltaics is a system that is currently being used in places like Europe, Japan, and parts of the United States, but it's still not common in most West African regions, especially in the rural areas [13–15]. The ideology entails the development of raised solar panels at a few meters high to enable the growing of crops underneath them. This way, the same land produces both food and electricity. For rural areas in Nigeria, this approach could help solve two problems at once. The solar panels would generate power that could be used for things like cold storage, cassava processing, rice milling, and even making tomato paste. It could also run water pumps for boreholes, reducing the need for diesel generators. At the same time, the partial shade from the panels could actually help certain crops that struggle under very intense sunlight.

Relatively, theory and on-ground reality often diverge. Most existing research on agrivoltaics in Africa has concentrated on large-scale solar farms or biophysical measurements of crop performance under photovoltaic panels [16–19]. However, a growing body of empirical work has examined farmer perceptions and social acceptance of agrivoltaics on the continent. In Kenya, Cinderby et al. [16] found that smallholder farmers expressed positive attitudes toward dual land use, provided that grazing access was maintained and that clear benefit-sharing mechanisms were established. Similarly, in Nigeria, El-Rufai et al. [18] reported that willingness to adopt agrivoltaics was strongly mediated by perceived water security gains and the availability of local technical support, underscoring the importance of context-specific institutional arrangements even within the West African setting. These studies demonstrate that social acceptance is not automatic but depends on context-specific institutional arrangements. Yet none of these investigations were conducted in the humid, densely populated farming systems of West Africa, where rainfall is not the primary constraint but where chronic electricity deficits severely limit post-harvest processing and water pumping. Furthermore, these studies did not explicitly integrate food processing infrastructure (e.g., milling, cold storage) as part of the agrivoltaic value proposition; a critical omission in settings where post-harvest losses are driven more by lack of processing energy than by crop water stress.

Beyond social acceptance, a substantial body of agronomic research has documented crop yield responses under agrivoltaic conditions. Field trials by Fraunhofer ISE (Germany) and the U.S. Department of Energy's Argonne National Laboratory have demonstrated that partial shading from elevated solar panels can reduce heat stress and evapotranspiration, benefiting shade-tolerant or semi-tolerant crops such as lettuce, potatoes, and certain varieties of peppers and tomatoes [20, 21]. In drier climates, agrivoltaics have been shown to increase water productivity by 14–23% due to lower evaporation [22, 23]. These findings are directly relevant to the Anambra context, where high midday temperatures can exceed optimal ranges for vegetables like tomato and okra. Nevertheless, no study has yet translated these biophysical findings into a feasibility assessment for integrated agrivoltaic systems that simultaneously power food processing and water supply in a rural Nigerian setting.

Critically, the authors are aware of only one previous study that has specifically examined agrivoltaic potentials in Nigeria: Babarinde [24] provided a technical assessment of solar radiation, land availability, and crop compatibility, concluding that the country has significant theoretical capacity for agrivoltaic deployment. The present study therefore fills a distinct gap by providing the first empirical, stakeholder-centered investigation of agrivoltaics for food processing and water supply in rural Nigeria, based on survey data from 840 respondents in the Anambra agricultural zones.

Most of the recent studies conducted in Nigeria have focused on solar-powered irrigation as a separate solution [25, 26], with complementary techno-economic analyses of standalone photovoltaic systems further demonstrating the financial feasibility of solar energy deployment in Nigerian institutional and agricultural contexts [27]. That helps to some extent, but it does not address the bigger picture. A farmer may be able to water crops yet still have no way to process or preserve the harvest afterwards. There are also solar dryers in use, but they tend to operate independently, disconnected from water systems or other farm infrastructure. Agrivoltaics attempts to integrate these functions, but so far no research has systematically assessed how communities in places like Anambra; or similar humid, electricity-poor farming areas, perceive the trade-offs involved. Key uncertainties remain around farmer acceptance of reducing cultivable land (or sharing it with elevated panels), trust in how generated electricity would be managed and allocated for processing equipment rather than diverted for other uses, and the economic viability of such systems for households living on very low daily incomes.

This research was conducted within the four agricultural zones of Anambra State, which lie in the tropical rainforest belt of southeastern Nigeria. While Anambra shares many characteristics with other rural, electricity-deficient areas in the country, such as reliance on diesel generators, high post-harvest losses, and chronic grid instability, it differs significantly from semi-arid or Sahelian regions (e.g., Sokoto, Borno, Kebbi) in terms of rainfall patterns, crop portfolios, and land tenure arrangements. Moreover, the sampling frame was drawn from registered farmers under the Agricultural Development Program in the State. In Nigeria, many rural farmers, particularly women, youth, and those in remote hamlets, are not formally registered with extension services. This introduces potential coverage bias, as unregistered farmers may have different energy access profiles, land security, and attitudes toward new technologies. Therefore, while the findings provide valuable insights for Anambra and similar humid, electricity-poor zones of southern Nigeria, they should not be generalized to the entire country without further validation through comparative studies across different agro-ecological zones.

The main objective of this case study was therefore to explore how stakeholders in the Anambra Agricultural Zones perceive the potential of agrivoltaic systems to improve food processing capacity and make water supply more reliable. It also examined the current state of rural electrification and how it affects post-harvest activities and water pumping, alongside stakeholders' willingness to adopt agrivoltaic technology within their existing farming systems. The study further assessed how agrivoltaics is perceived to influence improvements in food processing efficiency and water availability, as well as the main factors that could either hinder or support its adoption in the area. By engaging directly with farmers, food processors, and water facility operators, this research provides the first empirical baseline for agrivoltaic planning in southeastern Nigeria.

1.1 Theoretical Framework

To move beyond descriptive reporting of adoption willingness, this study draws on the Davis' Technology Acceptance Model (TAM) reported by Badda [28]. This is one of the most widely applied frameworks for understanding user acceptance of new technologies. TAM posits that two primary cognitive constructs drive behavioural intention to adopt a technology: perceived usefulness (the degree to which a person believes that using the technology would enhance their performance or outcomes) and perceived ease of

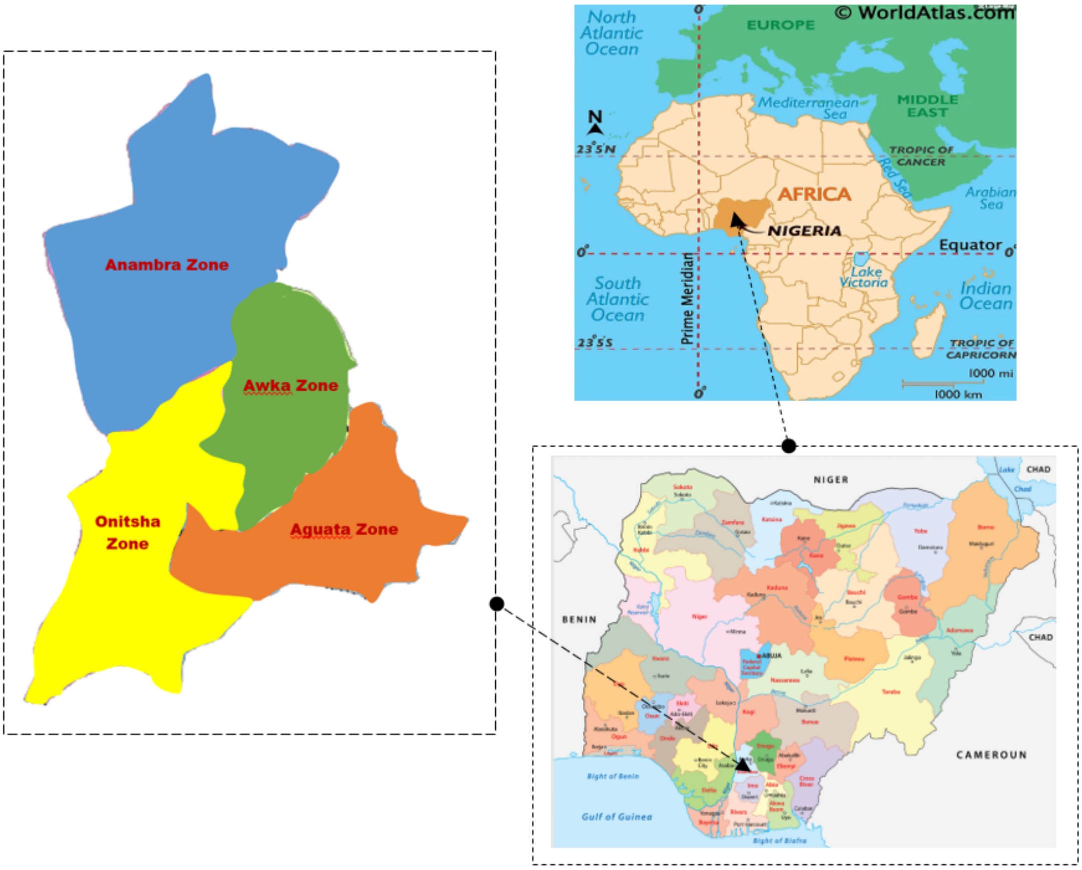

Figure 1. Map showing the four agricultural zones of Anambra State. (Aguata, Awka, Anambra, and Onitsha) surveyed in this study. These zones span the tropical rainforest belt of southeastern Nigeria.

use (the degree to which a person believes that using the technology would be free of effort). These perceptions are influenced by external variables (e.g., social influence, facilitating conditions, prior experience) and ultimately determine actual usage behaviour. TAM is particularly appropriate for agrivoltaic adoption in rural Nigeria because:

1. the technology is novel to the study area, making initial perceptions critical;
2. adoption is voluntary rather than mandatory; and
3. previous agricultural technology studies in developing countries have successfully applied TAM to explain adoption of solar irrigation, improved seeds, and digital extension services.

In the context of this study, perceived usefulness corresponds to respondents' beliefs that agrivoltaics will improve food processing efficiency and water supply reliability (Y_1 and Y_2 composite scores). Perceived ease of use is reflected in items related to technical complexity, maintenance burden, and land tenure security (e.g., "Frequent heavy rains and winds would damage solar panels," "I would need extensive training to use the system"). External variables include socio-demographic factors (income, occupation, electricity access) and contextual factors (prior exposure to solar technology, community leadership).

The study does not claim to test the full TAM model quantitatively. Instead, TAM constructs are used qualitatively to frame the interpretation of results – particularly the observed barriers (high cost, lack of technical awareness, land tenure insecurity) and the strong association between willingness and perceived improvements. TAM also guided the selection of perception items (e.g., perceived usefulness proxies, ease-of-use concerns, social influence, facilitating conditions). Section 3.8 presents an exploratory factor analysis to assess whether the measured items empirically align with TAM's latent constructs, but these factor scores are not entered into the regression models. The regression analysis instead focuses on the association between a composite willingness index (behavioural intention proxy) and perceived improvements, controlling for socio-economic covariates.

2 Materials and Methods

2.1 Study area description

The research was carried out in the four (Aguata, Awka, Anambra and Onitsha) Agricultural Zones of Anambra State, located in the southeastern region of Nigeria. The state shares administrative borders with Delta State to the west, Imo and Abia States to the south, Enugu State to the east, and Kogi State to the north (Figure 1).

These zones feature a humid tropical climate characterized by distinct wet/rainy (April to October) and dry (November to March) seasons, supporting fertile agro-ecological belts well-suited for arable crop production, primarily yam, cassava, maize, and rice [29]. Agricultural information access in these communities varies considerably by gender, a pattern documented across southeastern Nigerian farming systems [30]. Average annual rainfall of the State ranges from 1639.40 to 3863.40 mm [31], while temperatures vary approximately between 26 °C and 30 °C throughout the year [32]. The area supports a dense farming population, with average farm holdings between 0.5 and 2.0 hectares per household [33–35]. The mean rural electrification rates, according to Nigerian Energy Support Programme (NESP) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH [36], stand at approximately 35%, and most functional electricity connections rely on illegal tapping from distribution lines, leading to frequent disconnection.

2.2 Research design

This study adopted a cross-sectional survey approach, which made it possible to gather quantitative data from a sample of the target population at a single point in time. The design was suitable for capturing people's current views, attitudes, and willingness to adopt a new technology without the need for long-term observation or experimentation. Data for the study were collected using a structured questionnaire.

2.3 Population and sampling

The population of the study is principally the 22,056 Agricultural Development Program (ADP) registered farming households in Anambra State [37]. A limitation of this sampling frame is that it includes only farmers formally registered with the ADP extension system. In rural Anambra, many smallholder farmers; particularly women, youth, and those in hamlets without extension presence, are not registered. Consequently, the sampling frame may underrepresent these groups, introducing potential coverage bias. The study partially mitigated this by supplementing the ADP list with community-level sampling during the final stage, but the extent to which unregistered farmers differ in their perceptions of agrivoltaics remains unknown and should be addressed in future research. To determine an appropriate sample size for a multi-stage cluster sampling design, the standard formula for cluster surveys was used:

$$n = \left[\frac{Z^2 \times p \times (1-p)}{e^2}\right] \times DE \tag{1}$$

where, n = required sample size, Z = Z-score corresponding to confidence level (1.96 for 95% confidence), p = maximum variability (0.5), $(1-p)$ = complement of the proportion, e = margin of error (0.05), DE = typical design effect for multi-stage cluster sampling in rural agricultural settings (2.0).

$$\begin{aligned} \therefore n &= \left[\frac{1.96^2 \times 0.5 \times (1-0.5)}{0.05^2}\right] \times 2 \\ &= \left[\frac{3.842 \times 0.25}{0.0025}\right] \times 2 \\ &= 384.2 \times 2 \\ &= 768.4 \end{aligned} \tag{2}$$

To account for anticipated non-response or incomplete questionnaires (approximately 10%), the target sample size was increased to 845 respondents.

A multi-stage sampling procedure was adopted to identify the final respondents for the study.

1. In the first stage, all four agricultural zones in Anambra State: Aguata, Awka, Anambra, and Onitsha, were purposively included to ensure full geographic coverage of the state's farming system.
2. In the second stage, two Local Government Areas (LGAs) were selected from each agricultural zone based on their strong agricultural activity, giving a total of eight LGAs: Nnewi South, Orumba North, Dunukofia, Njikoka, Anambra East, Oyi, Idemili North, and Ihiala.
3. The third stage involved the selection of two farming communities from each of the chosen LGAs, resulting in 16 communities altogether.
4. Finally, in the fourth stage, farming households were selected from the sampled communities with

the estimated sampling frame of 22,056 farming households across all selected communities acting as reference or guide.

To obtain a representative total sample size of 845 respondents, the number of participants assigned to each community (n_i) was determined using a Probability Proportional to Size (PPS) allocation method. This ensures that communities with larger farming populations contribute more respondents than smaller ones. The allocation was computed using the formula:

$$n_i = \left(\frac{N_i}{N}\right) \times n \tag{3}$$

where, n_i = number of farming household respondents allocated to sample community, N_i = estimated population of farming households within sample community, N = total population of farming households across all 16 communities (22,056), n = total targeted survey sample size (845).

The allocation of the study sample across the selected agricultural strata is presented in Table 1. It shows how the total sample size was proportionally distributed among the sampled communities based on their estimated farming household populations. To ensure high data spatial accuracy, geographic coordinates (latitude and longitude) were recorded at the central node of each community using hand-held Global Positioning System (GPS) receivers.

2.4 Questionnaire Design and Structure

The questionnaire was divided into five sections. It gathered basic background information, measured key constructs using Likert-scale items, and included specific questions on land tenure and benefit-sharing.

2.4.1 Background Information

The questionnaire first collected basic respondent demographics and contextual data, including:

i Age, gender, main occupation, years of farming experience, household size, and estimated monthly income.

ii Current energy sources relied upon (e.g., grid electricity, generators, batteries, kerosene).

iii Estimated proportion of harvest typically lost due to limited processing options or lack of cold storage.

iv Water access details: average daily hours of water availability and the primary energy source for pumping.

v To cross-validate perceived post-harvest loss estimates, respondents were asked a categorical question: *"In your opinion, what proportion of your tomato/vegetable harvest is typically lost within 48*

Table 1. Distribution of sample across agricultural zones, LGAs, and communities (probability-proportional-to-size sampling).

Zone	L.G.A.	Community	GPS Coordinates	Estimated Farming Households (N)	Allocated Respondents (n)
Aguata	Nnewi South	Unubi	5.9634°N, 7.0431°E	1,850	78
		Ekwulumili	5.9775°N, 7.0188°E	1,620	68
	Orumba North	Amaokpala	6.0333°N, 7.1167°E	980	41
		Okpeze	6.0064°N, 7.1658°E	1,150	49
Awka	Dunukofia	Ifitedunu	6.1901°N, 6.8773°E	1,450	61
		Ukwulu	6.2724°N, 6.9608°E	890	38
	Njikoka	Abba	6.2181°N, 6.9787°E	2,100	89
		Enugwu-Agidi	6.2200°N, 7.0111°E	1,780	75
Anambra	Anambra East	Umuoba-Anam	6.3370°N, 6.8390°E	1,250	53
		Aguleri	6.3286°N, 6.8825°E	1,960	83
	Oyi	Umunya	6.1774°N, 6.8623°E	870	37
		Nteje	6.2681°N, 6.9206°E	1,440	61
Onitsha	Idemili North	Uke	6.1086°N, 6.9290°E	1,050	44
		Abacha	6.1432°N, 6.9569°E	920	39
	Ihiala	Okija	5.9161°N, 6.8167°E	1,280	54
		Uli	5.8597°N, 6.8600°E	1,466	62
Total	**4 Zones**	**16 Communities**		**22,056**	**845**

Source: Field Survey, 2026

hours of harvesting?" with response options: (a) Less than 10%, (b) 10–20%, (c) 21–30%, (d) 31–40%, (e) More than 40%. For cassava, a similar question was asked regarding spoilage within 5 days of harvest.

vi For water supply, respondents were asked: *"During the most recent dry season, how many days in a row did you go without access to pumped water from your primary source?"* (open-ended numeric response).

vii For food processing, respondents were asked: *"On average, how many times per week do you or your household use a motorized mill or grater?"* (numeric response).

2.4.2 *Core Attitude and Perception Items (5-Point Likert Scale)*

Attitude and perception items were measured on a 5-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The key Likert-based statements included:

i The current electricity supply in the community is sufficient for food processing activities.

ii Installing solar panels above farmland could provide reliable power for processing cassava, rice, and other crops without reducing available farmland.

iii A shared agrivoltaic system would improve access to pumped water for both household use and irrigation.

iv There is willingness to contribute labour or pay a small monthly fee to support the maintenance of an agrivoltaic system in the community.

v The high initial cost of solar equipment is the main challenge to adopting agrivoltaic systems in the study area.

vi Frequent heavy rains and winds in this area would damage solar panels or make them unsafe.

vii Dust, Harmattan haze, and bird droppings would make it difficult to keep solar panels clean enough to generate power effectively.

viii Learning to operate and maintain an agrivoltaic system would be easy for me or someone in my community (perceived ease of use).

ix An agrivoltaic system would require too much daily effort to keep clean and working properly (reverse-coded for perceived ease of use).

x If my neighbours or community leaders adopted agrivoltaics, I would be more willing to adopt it as well (social influence / subjective norm).

xi I believe the government or NGOs would provide the necessary support (training, spare parts, financing) to make agrivoltaics work here (facilitating conditions).

2.4.3 *Operationalization of key study variables (multi-item scales)*

To operationalize key study variables, the research adopted multi-item measurement scales for data collection and construct assessment.

The first dependent construct (Y_1) assessed respondents' perceived improvement in food processing efficiency, measured through a composite score derived from four indicator items (score range: 4–20). Specifically, this construct captured respondents' perceptions of the potential contribution of agrivoltaic systems to agricultural processing activities across four dimensions: (i) reduction in post-harvest cassava spoilage; (ii) increased availability of evening processing hours facilitated by extended lighting; (iii) improved access to electrically powered milling facilities within rural communities; and (iv) reduced reliance on diesel-powered processing equipment. Higher composite scores indicated stronger perceived positive impact of agrivoltaic system adoption on food processing efficiency.

The second dependent construct (Y_2) measured respondents' perceived improvement in water supply reliability, assessed through a composite score comprising four indicator items (score range: 4-20). This construct evaluated respondents' perceptions of the capacity of agrivoltaic systems to enhance water accessibility and supply consistency across four dimensions: (i) consistency of daily water pumping operations; (ii) reduced frequency of water shortages during dry-season periods; (iii) extended availability of borehole water supply throughout the year; and (iv) decreased distance travelled by households for water collection. Higher composite scores reflected stronger perceived positive impact of agrivoltaic system adoption on water supply reliability.

The first independent construct (X_1) assessed respondents' willingness to adopt agrivoltaics, quantified through a composite score aggregated from three indicator items (score range: 3–15). This construct captured respondents' behavioural intention and readiness to participate in agrivoltaic implementation across three dimensions: (i) willingness to permit the installation of solar panels on personal farmland; (ii) willingness to contribute labour during the system implementation process; and (iii) willingness to provide financial support through contributions to ongoing maintenance activities. All measurement items were evaluated using a uniform five-point Likert-type scale, ranging from 1 (*Strongly Disagree*) to 5 (*Strongly Agree*). Composite indices for each construct were subsequently derived by aggregating individual item responses across their respective indicator items.

2.4.4 Land access and benefit-sharing preferences

Recognizing that customary land tenure systems are a potential barrier to long-term agrivoltaic adoption, the questionnaire included a dedicated section on land access and benefit-sharing preferences.

Based on key informant consultations and a systematic review of land tenure literature pertaining to southeastern Nigeria, four additional items were developed using a five-point Likert-type scale (1 = *Strongly Disagree* to 5 = *Strongly Agree*) to assess respondents' perceptions and attitudes toward land tenure arrangements in the context of agrivoltaic adoption. The items addressed the following dimensions: (i) perceived security of land use rights, specifically whether respondents held secure rights to cultivate their current farmland for a period of ten years or more; (ii) openness to installing solar panels on communal land, contingent upon a collective community decision; (iii) willingness to permit solar panel installation on family-owned farmland in exchange for an equitable share of the electricity generated or the associated income; and (iv) normative beliefs regarding the equitable distribution of electricity benefits derived from agrivoltaic systems, reflecting the view that such benefits should accrue to the broader community rather than exclusively to the landowner. These items were designed to capture the multidimensional nature of land tenure security and community governance norms as potential mediating factors in agrivoltaic adoption decisions.

To capture the nuanced nature of prevailing land tenure arrangements, two open-ended questions were incorporated into the survey instrument. The first question asked respondents to identify their primary arrangement for accessing farmland, with the following predefined response options: (a) family-owned land; (b) communally allocated land; (c) land rented from another household; (d) informally occupied land without formal permission (squatter arrangement); and (e) other arrangements not covered by the preceding categories. The second question invited respondents to express their views on benefit distribution by asking: *"If agrivoltaic panels were installed on land you use, who do you believe should receive the majority of the benefits?"* These items were designed to enable an empirical assessment of the prevalence of tenure insecurity among the study population and its potential moderating effect on respondents' willingness to adopt agrivoltaic systems.

To minimise non-response rates and ensure accurate comprehension of technical terminology, trained field enumerators who were fluent in both English and the Igbo language administered the questionnaires to all respondents, following established practice in Nigerian rural agricultural surveys where linguistic accessibility has been shown to be critical for reaching farmers with varying levels of formal education [30]. This bilingual administration protocol was considered essential given the technical nature of agrivoltaic concepts and the linguistic diversity of the study communities in southeastern Nigeria.

2.5 Validity and reliability

Content validity was ensured by presenting the draft questionnaire to a panel of three experts: a Professor of Agricultural Engineering from Nnamdi Azikiwe University, Awka, a rural sociologist, and an extension officer familiar with the study area. They reviewed each item for relevance, clarity, and suitability, and any questions considered unclear or unnecessary were either revised or removed. Construct validity was examined through a pilot study carried out in a non-study community, Ekwulobia in Aguata LGA, involving 40 respondents with similar characteristics to those in the main study. The responses from this pilot were analyzed to confirm that the Likert-scale items grouped in a consistent and meaningful way.

To check reliability, Cronbach's alpha (α) coefficient was used. The alpha values for the different sections ranged between 0.76 and 0.91, indicating good internal consistency across the instrument. The four land tenure items together produced a Cronbach's α of 0.76, and the four TAM items (perceived usefulness proxy, ease of use, social influence, facilitating conditions) produced $\alpha = 0.82$, acceptable for exploratory research.

2.5.1 *Exploratory factor analysis (EFA) for theoretical validation*

To assess whether the measured items empirically align with the Technology Acceptance Model's latent constructs, an exploratory factor analysis was conducted on the 23 perception items using principal axis factoring with oblique rotation (Promax). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.84, and Bartlett's test of sphericity was significant ($\chi^2 = 2,847.6$, $p < 0.001$), indicating that the data were suitable for factor analysis. Based on eigenvalue > 1.0 and inspection of the scree plot, a four-factor solution emerged, explaining 58.3% of the total variance. Factor loadings are presented in Section 3.8. The factor structure broadly corresponded to theoretical expectations: Factor 1 grouped items related to perceived usefulness for food processing and water supply (eigenvalue = 6.42, 27.9% variance); Factor 2 grouped items related to barriers (cost, theft, technical complexity) and low perceived ease of use (eigenvalue = 3.18, 13.8% variance); Factor 3 grouped land tenure and benefit-sharing items (eigenvalue = 2.05, 8.9% variance); Factor 4 grouped social influence and facilitating conditions items (eigenvalue = 1.67, 7.3% variance). No item cross-loaded above 0.40 on multiple factors. These results provide preliminary empirical support for applying TAM-like constructs in the agrivoltaic adoption context, though the study is exploratory and does not claim to validate the full TAM model.

2.6 Data collection procedure

Field data collection was carried out over a ten-week period, from February 15, 2026 to April 26, 2026. Five trained enumerators, who were fluent in both English and Igbo, conducted the survey through face-to-face interviews. This approach was necessary because literacy levels in the study area are quite varied, so it could not be assumed that all respondents would be able to read or write comfortably. During each interview, the enumerators read the questions aloud in Igbo, showed respondents the printed Likert scale, and recorded their selected responses. Each session typically lasted between 25 and 40 minutes. Verbal informed consent was obtained before starting, and participants were assured that their involvement was voluntary and that their identities would remain confidential. In total, 845 questionnaires were administered. Of these, 5 were excluded during data cleaning due to significant missing data or patterned responses, leaving 840 valid questionnaires for analysis (840/845 = 99.4%).

2.7 Data analysis techniques

Data analysis was carried out using SPSS version 26 and Stata 17. Descriptive statistics, including frequencies, percentages, means, and standard deviations, were first computed for the demographic variables and Likert scale responses. For the Likert items, a mean score above 3.0 was taken to indicate agreement or a positive perception, while a mean below 3.0 suggested disagreement. To examine the relationship between willingness to adopt agrivoltaic technology and the selected outcome variables; food processing efficiency and water supply reliability, ordinal logistic regression analysis was employed. The outcome variables, perceived improvement in food processing efficiency (Y_1) and perceived improvement in water supply reliability (Y_2), were initially measured as composite indices with score ranges from 4 to 20. To facilitate ordinal modelling, the composite scores were subsequently categorized into three ordered groups representing low (4–9), moderate (10–14), and high (15–20) levels.

Given the ordinal nature of the dependent variables, the proportional odds model was considered appropriate for estimating the association between explanatory variables and respondents' likelihood of belonging to higher outcome categories. Prior to model estimation, the proportional odds assumption was evaluated using the Brant test to verify model suitability.

The first regression model estimated associations between selected explanatory variables and perceived improvement in food processing efficiency, specified as:

$$\operatorname{logit}(P(Y_1 \leq j)) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \varepsilon \tag{4}$$

where: Y_1 = perceived improvement in food processing efficiency (categorized as low, moderate, and high), X_1 = willingness to adopt agrivoltaics, measured as a composite index and treated as a continuous predictor following assessment of linearity assumptions, X_2 = current electricity access, measured as average daily hours of electricity supply, X_3 = primary occupation, coded as a binary variable (1 = food processor; 0 = otherwise), X_4 = household monthly income measured in Nigerian Naira and logarithmically transformed to minimize skewness, ε = random error.

The second regression model estimated associations between selected explanatory variables and perceived improvement in water supply reliability, specified as:

$$\text{logit}(P(Y_2 \leq j)) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \varepsilon \quad (5)$$

where: Y_2 = perceived improvement in water supply reliability (categorized as low, moderate, and high), X_1 = willingness to adopt agrivoltaics, X_2 = current electricity access, X_3 = current water source, coded as a binary variable (1 = borehole; 0 = well/stream), X_4 = distance to the primary water source measured in kilometres, ε = random error.

Model adequacy was assessed through the proportional odds assumption test using the Brant procedure. In addition, model fit statistics were evaluated using McFadden's Pseudo R^2. Statistical inference was based on a 5 percent significance level ($p < 0.05$). Data analysis and model estimation were conducted using Stata version 17 utilizing the ordinal logistic regression (logit) procedure together with relevant post-estimation diagnostics. Gender was not included as an independent variable in regression models due to sample size limitations relative to the number of predictors, and because preliminary bivariate analyses showed no significant gender-based differences in the outcome variables ($p > 0.10$ for all comparisons). Future studies with larger samples should examine gender interaction effects.

The cross-sectional nature of this study precludes causal inference. Two sources of endogeneity are of particular concern. First, reverse causality is likely between willingness to adopt agrivoltaics (X_1) and perceived improvements (Y_1, Y_2): respondents who believe agrivoltaics will bring greater benefits are more likely to express high willingness, meaning the estimated association could be bidirectional. Second, omitted variables, such as general trust in new technologies, community leadership quality, prior exposure to solar projects, or risk tolerance, may influence both willingness and perceived improvements, producing spurious associations.

To explore whether an instrumental variables (IV) approach could mitigate these concerns, two potential instruments were considered:

a "presence of a functioning solar-powered borehole or solar home system in the respondent's community" (a proxy for prior exposure to solar technology), and
b "distance to the nearest town with a solar equipment vendor" (a proxy for information access). However, both failed the exogeneity requirement. The first instrument was correlated with the error term because communities with existing solar infrastructure may have systematically different unobserved characteristics (e.g., better community organization, higher income). The second instrument was weak (first-stage F-statistic = 4.2, below the conventional threshold of 10). Therefore, no valid instrument was available, and two-stage least squares could not be implemented.

All regression results reported in this study are associational, not causal. The terms "association," "correlate," "related to," or "odds ratio" were utilized throughout the manuscript. Hence the strength of associations (OR = 1.42, 1.53) should be interpreted as reflecting stated perceptions and willingness that may be bidirectional.

2.8 Ethical considerations

Ethical approval for this study was obtained from the Research Ethics Committee of the Department of Agricultural and Bioresources Engineering, Nnamdi Azikiwe University, Awka (Approval No. ABE/NAU/2025/ETH/002, dated 10 January 2026). Permission was also obtained from the traditional rulers of all 16 communities. This was done to ensure respect for local authority structures and to secure community-level approval for the research activities. All participants gave verbal informed consent after receiving a clear explanation of the study's purpose, voluntary participation, confidentiality, and the right to withdraw at any time without penalty. No personal identifiers were recorded or disclosed at any stage of the research.

3 Results and Discussion

3.1 Demographic profile of respondents

Among the 840 valid respondents, 51% were male and 49% were female, showing a fairly balanced gender distribution. This pattern reflects the shared but distinct roles in agriculture within Anambra, where men are often more involved in land preparation and produce marketing, while women play a major role in food processing and vegetable production. The mean age of respondents was 47.0 years (SD = 12.1), pointing to a relatively older farming population. This aligns with the common trend in rural Nigeria, where younger people are increasingly moving to urban

Table 2. Demographic characteristics of respondents (N = 840).

Variable	Category	Frequency (n)	Percentage (%)	Mean (SD)
Gender	Male	428	51.0	-
	Female	412	49.0	-
Age (years)	-	-	-	47.0 (12.1)
Primary occupation	Farming	596	71.0	-
	Food processing	160	19.0	-
	Water facility operation	84	10.0	-
Farming experience (years)	-	-	-	12.0 (9.4)
Household size (persons)	-	-	-	6.0 (2.1)
Monthly income (₦)	Median	38,000	-	-
	Range	8,000 – 150,000	-	-

Source: Field survey, 2026

areas in search of non-farm employment. Farming remained the main occupation for 71% of respondents, while 19% were primarily engaged in food processing activities such as cassava grating, rice milling, and palm oil extraction. The remaining 10% were involved in managing or operating water facilities.

Respondents reported an average farming experience of 12.0 years, indicating a strong base of indigenous knowledge, though this may also come with a level of reluctance toward unfamiliar innovations. The average household size was 6.0 persons, reflecting the prevalence of extended family systems in the area. Income levels varied considerably, with a median monthly income of about ₦38,000.00, reflecting the broader economic constraints faced by smallholder households in southeastern Nigeria, where financial limitations have been identified as a key barrier to the adoption of sustainable land and agricultural management practices [38]. Table 2 presents the full demographic characteristics.

3.2 Current rural electrification status

Only 14.5% of respondents reported having access to grid electricity at either their home or place of work. For those connected, the average daily supply was about 3.2 hours, often occurring late at night when it is not useful for food processing activities. Generator ownership was higher at 32%, although high fuel costs meant they were typically used for only about 2.5 hours per day on average. In terms of lighting, most households relied on battery-powered torches (67%), which were used for roughly 11 hours daily. This was followed by kerosene lanterns (11%), with an average usage of about 6 hours per day (Figure 2).

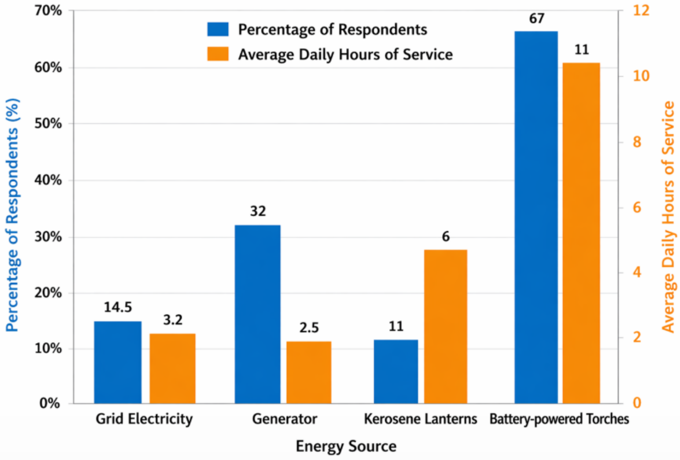

Figure 2. Bar chart comparing current energy sources and average daily hours of service.

For food processing, most activities were still done through motorized services outside the community. About 83% of respondents reported that cassava grating and 91% that grain milling are currently carried out in nearby towns where diesel- or petrol-powered mills are available. This finding describes existing coping strategies but does not predict whether agrivoltaic systems would replace these services, as that would depend on comparative cost, convenience, trust relationships with mill operators, and the reliability of locally generated solar power. Post-harvest losses were also significant. Around 67% of respondents estimated losing at least 20% of their vegetable harvest within 48 hours of harvesting. For fresh cassava roots, which typically spoil within 3–5 days, 29% reported similar levels of loss. Among tomato farmers, 52% indicated that they lose more than 30% of each harvest due to the absence

Table 3. Mean scores and standard deviations for Likert-scale items (N = 840).

Item No.	Statement	Mean	SD	Interpretation
1	Current electricity supply is sufficient for food processing.	1.78	0.89	Disagree
2	Agrivoltaics could power processing without losing farmland.	4.21	0.76	Agree
3	Shared agrivoltaic system would improve water access.	4.53	0.68	Strongly agree
4	Willingness to contribute labour or fee for maintenance.	3.94	0.92	Agree
5	High upfront cost is the main barrier.	4.38	0.71	Agree

Likert scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree

of refrigeration facilities.

In terms of water supply, 13% of households depended on hand-pumped boreholes that require manual effort to operate. Another 35% relied on electric boreholes, which only function when grid electricity is available or when fuel is used to run generators. About 13% reported access to solar-powered constituency project boreholes, while 39% still depended on streams or shallow wells for their daily water needs. For those using electric boreholes, the average daily water availability was only about 3.2 hours. This situation becomes even worse during the dry season, when some communities experience interruptions lasting up to two weeks without any pumped water. The consequences for hygiene, drinking water quality, and dry-season irrigation are quite serious.

3.3 Descriptive results on likert-scale responses

Table 3 presents the mean scores and standard deviations for the five key Likert items. The strongest level of agreement was observed for Item 3, which stated that a shared agrivoltaic system would improve water access (mean = 4.53, SD = 0.68). This was followed by Item 5, where respondents identified high upfront cost as the main barrier (mean = 4.38, SD = 0.71). In contrast, Item 1, which assessed whether current electricity supply is sufficient, recorded the lowest mean score (mean = 1.78, SD = 0.89), indicating clear disagreement among respondents. Item 4, relating to willingness to contribute labour or a fee, showed comparatively greater variation (mean = 3.94, SD = 0.92), with approximately 18% of respondents expressing disagreement.

To assess the consistency of subjective perception responses, selected Likert items were cross-validated against categorical and numeric questions. Among respondents who "agreed" or "strongly agreed" that post-harvest losses are substantial (Item 1 related to losses, though not shown in Table 3, was asked separately), 82% selected loss categories of 21–30% or higher for tomatoes/vegetables, and 76% selected similar categories for cassava. Conversely, among those who "disagreed" or "strongly disagreed" with loss statements, only 18% selected high loss categories ($\chi^2 = 34.2, p < 0.001$), indicating acceptable correspondence between Likert perceptions and categorical estimates.

Regarding water supply, respondents who "strongly agreed" that water access is unreliable (Item 1 in Table 3 is about electricity, not water; a separate water reliability item was asked) reported a mean of 9.4 consecutive days without pumped water during the last dry season ($SD = 6.2$), compared to 2.1 days ($SD = 1.8$) among those who disagreed ($t = 12.4, p < 0.001$). These cross-validations suggest that the perception data are broadly consistent with more concrete recall-based estimates, although recall bias remains a limitation.

The quantitative results were further supported by qualitative comments from respondents. For example, a woman in Abba remarked, "If I could turn a switch and have water come out, I would have time to do two extra things every day, maybe start a small tomato paste business." Such responses highlight the practical value respondents place on reliable water access. In relation to Item 2, some older farmers initially raised concerns about the possibility of losing farmland to solar panel installations. However, after the concept of elevated panel structures was explained, many became more open to the idea. The shading effect also drew interest, particularly among vegetable farmers, who noted that certain crops tend to be struggling under intense midday sunlight.

3.4 Land tenure arrangements and perceptions

Understanding land access is essential for assessing the feasibility of agrivoltaic systems, which require long-term occupation of arable land. Table 4 summarizes respondents' land access arrangements. The majority (58%) relied on family-owned land, while 23% cultivated on communal land with use rights granted by village councils or extended family heads. Rented land accounted for 12% of respondents, and 7% reported farming as squatters or without formal permission. These figures indicate that while most respondents have some recognized use rights, a substantial minority (19%, combining renters and squatters) face insecure tenure that could discourage investment in fixed infrastructure. It further reflects the predominance of smallholder farming systems, which are increasingly characterised by declining farm sizes across sub-Saharan Africa [35].

Table 4. Land access arrangements among respondents (N = 840).

Arrangement	Frequency (n)	Percentage (%)
Family-owned land	487	58.0
Communal allocation	193	23.0
Rented from another household	101	12.0
Squatter / no formal permission	59	7.0

Source: Field survey, 2026

When asked about willingness to host agrivoltaic panels under different tenure scenarios (Table 5), respondents expressed the highest agreement for installation on communal land subject to collective decision-making (mean = 4.12, SD = 0.85). Agreement was somewhat lower for installation on family-owned land in exchange for a share of benefits (mean = 3.78, SD = 0.94), and substantially lower among respondents who reported renting or squatting (mean = 2.56, SD = 1.12, data not tabulated). Regarding benefit distribution, a strong majority agreed that electricity should benefit the whole community equally rather than accrue only to the landowner (mean = 4.34, SD = 0.72). Open-ended responses revealed concerns that landowners might appropriate most of the generated power or income, leaving other community members with little gain. One respondent in Aguleri stated, *“If the panels go on my brother’s land, he will take the electricity for his freezer and leave us with nothing. It must be for everyone or not at all.”*

3.5 Perceived technical and environmental risks of agrivoltaics

Table 6 presents respondents’ perceptions of natural and technical risks associated with agrivoltaic systems in the study area. The highest level of concern was expressed regarding the potential for heavy rains and high winds to damage elevated solar panels (mean = 4.18, SD = 0.82), reflecting local experience with seasonal thunderstorms and occasional windstorms that damage roofs and crops. Concerns about soiling from dust, Harmattan haze, and bird droppings were also substantial (mean = 3.95, SD = 0.91), with many respondents noting that even existing solar-powered boreholes in nearby communities often become less effective due to lack of regular cleaning.

Regarding battery storage, respondents with prior experience using solar products (e.g., solar home systems, solar boreholes) reported that lithium-ion batteries frequently fail within 6–10 years under local conditions, and replacement costs are often prohibitive. One respondent in Uli stated, “We had a solar borehole installed by a politician. After two years, the batteries died. Nobody could afford to replace them. Now it is just scrap metal.” When asked about willingness to pay for periodic battery replacement, the mean score was low (2.34, SD = 1.05), indicating that maintenance costs are a serious perceived barrier. Regarding crop performance under continuous shading, respondents expressed uncertainty. While vegetable farmers acknowledged that some crops (e.g., okra, amaranthus) might benefit from reduced midday heat stress, they were concerned about staple crops such as cassava and yam, which they believed require full sunlight. Only 34% of respondents agreed that “most local crops would grow well under the partial shade of solar panels”

Table 5. Perceptions of land tenure and benefit-sharing for agrivoltaic adoption (N = 840).

Statement	Mean	SD	Interpretation
"I have secure rights to use my farmland for the next 10+ years"	2.95	1.08	Neutral
"I would allow panels on communal land if the community decides collectively"	4.12	0.85	Agree
"I would allow panels on family-owned land in exchange for a share of benefits"	3.78	0.94	Agree
"Electricity should benefit the whole community equally, not just the landowner"	4.34	0.72	Strongly agree

Likert scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree

Table 6. Perceptions of technical and environmental risks (N = 840).

Statement	Mean	SD	Interpretation
"Heavy rains and high winds would damage solar panels or make them unsafe"	4.18	0.82	Agree
"Dust, Harmattan haze, and bird droppings would make it hard to keep panels clean"	3.95	0.91	Agree
"I would be willing to pay for battery replacement every 6–10 years"	2.34	1.05	Disagree
"Most local crops would grow well under partial shade of solar panels"	2.87	0.98	Neutral

Likert scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree

(mean = 2.87, SD = 0.98). Several respondents requested demonstration plots before committing land to agrivoltaic installations.

3.6 Regression analysis results

3.6.1 *Association between agrivoltaic adoption willingness and perceived food processing efficiency*

The first ordinal logistic regression model was estimated to examine the association of willingness to adopt agrivoltaics (X_1), current access to electricity (X_2), primary occupation as a food processor (X_3), and household income transformed into logarithmic form (X_4) on perceived improvements in food processing efficiency (Y_1). The overall model was statistically significant ($\chi^2(4) = 78.34$, $p < 0.001$), indicating that the explanatory variables jointly contributed to variations in respondents' perceptions. The model produced a McFadden pseudo R^2 value of 0.187, suggesting an acceptable level of explanatory power. Furthermore, the proportional odds assumption was satisfied, as indicated by the non-significant Brant test result ($\chi^2 = 6.21$, p = 0.62).

Among the explanatory variables, willingness to adopt agrivoltaics showed the strongest association of perceived food processing efficiency (OR = 1.42, 95% CI: 1.21–1.67, $p < 0.001$). This suggests that higher willingness is associated with higher odds of respondents reporting higher levels of perceived processing improvement. Access to electricity also showed a positive and statistically significant association (OR = 1.09, 95% CI: 1.02–1.17, p = 0.012), although the magnitude of the effect was relatively small. Conversely, occupation as a food processor (OR = 1.14, 95% CI: 0.93–1.40, p = 0.21) and household income (OR = 1.05, 95% CI: 0.96–1.15, p = 0.31) did not significantly explain differences in perceived food processing efficiency among respondents.

3.6.2 *Association between agrivoltaic adoption willingness and perceived water supply reliability*

The second ordinal logistic regression model investigated the relationship between perceived improvements in water supply reliability (Y_2) and selected explanatory variables including willingness to adopt agrivoltaics (X_1), electricity access (X_2), type of water source (X_5), and distance to the nearest water source (X_6). The model was statistically significant ($\chi^2(4) = 104.27$, $p < 0.001$), suggesting that the explanatory variables significantly predicted respondents' perceptions of water reliability. The model recorded a McFadden pseudo R^2 value of 0.241. Results from the Brant test confirmed that the proportional odds assumption was not violated ($\chi^2 = 7.83$, $p = 0.45$). Consistent with the previous model, willingness to adopt agrivoltaics had the strongest association with perceived water reliability (OR = 1.53, 95% CI: 1.30–1.80, $p < 0.001$), indicating that respondents with higher adoption willingness were more likely to report stronger perceived improvements in water supply reliability.

Access to electricity demonstrated a positive and statistically significant relationship with perceived water reliability (OR = 1.07, 95% CI: 1.00–1.14, $p = 0.045$). Similarly, water source type significantly influenced perceptions, as respondents relying primarily on boreholes were more likely to report higher perceived improvements than those depending on streams or wells (OR = 1.38, 95% CI: 1.18–1.62, $p < 0.001$). Distance to water source showed an inverse relationship with perceived improvements (OR = 0.82, 95% CI: 0.74–0.91, $p < 0.001$) (Table 7), suggesting that longer travel distances are associated with lower perceived improvements in water supply reliability.

All reported odds ratios reflect associational

Table 7. Summary of ordinal logistic regression results for predictors of perceived improvements in food processing efficiency (Y_1) and water supply reliability (Y_2).

Predictor	**Y_1: Food processing efficiency**		**Y_2: Water supply reliability**	
	OR (95% CI)	p	**OR (95% CI)**	p
Willingness to adopt agrivoltaics (composite, 3–15)	1.42 (1.21–1.67)	<0.001	1.53 (1.30–1.80)	<0.001
Current electricity access (hours/day)	1.09 (1.02–1.17)	0.012	1.07 (1.00–1.14)	0.045
Primary occupation: food processor (vs. farmer)	1.14 (0.93–1.40)	0.21	—	—
Household income (log-monthly, ₦)	1.05 (0.96–1.15)	0.31	—	—
Water source type: borehole (vs. well/stream)	—	—	1.38 (1.18–1.62)	<0.001
Distance to water source (km)	—	—	0.82 (0.74–0.91)	<0.001
Model χ^2 (df)	78.34 (4), $p < 0.001$		104.27 (4), $p < 0.001$	
McFadden pseudo R^2	0.187		0.241	
Brant test (proportional odds)	$\chi^2 = 6.21, p = 0.62$		$\chi^2 = 7.83, p = 0.45$	

OR = odds ratio; CI = confidence interval. Statistically significant predictors ($p < 0.05$) are bolded in the original table.

Table 8. Exploratory factor analysis loadings (oblique rotation).

Item (abbreviated)	**Factor 1 (Usefulness)**	**Factor 2 (Barriers/Ease)**	**Factor 3 (Tenure)**	**Factor 4 (Social/Facilitating)**
Agrivoltaics would improve water access	0.81	0.12	0.08	0.05
Agrivoltaics would reduce post-harvest losses	0.76	0.14	0.11	0.02
Agrivoltaics would enable evening processing	0.73	0.09	0.06	0.10
Agrivoltaics would reduce diesel dependence	0.68	0.11	0.04	0.08
High upfront cost is main barrier	0.11	0.79	0.09	0.14
Fear of theft would prevent adoption	0.08	0.68	0.21	0.12
Lack of local repair capacity is a barrier	0.14	0.72	0.11	0.18
Frequent rains/winds would damage panels	0.06	0.61	0.15	0.09
Cleaning panels would be difficult	0.09	0.59	0.08	0.13
I have secure land rights for 10+ years	0.11	0.16	0.74	0.08
I would allow panels on communal land	0.18	0.09	0.69	0.21
Electricity should benefit whole community	0.14	0.12	0.71	0.15
If neighbours adopt, I would adopt	0.12	0.14	0.09	0.68
If community leaders support, I would adopt	0.08	0.11	0.11	0.65
Govt/NGO support would enable adoption	0.15	0.18	0.13	0.62

Extraction method: Principal axis factoring. Rotation method: Promax with Kaiser normalization. Only loadings > 0.40 shown. KMO = 0.84; Bartlett's test $\chi^2 = 2,847.6$, $p < 0.001$; total variance explained = 58.3%.

relationships only. Although the Technology Acceptance Model guided the interpretation of barriers and the selection of perception items, it was not quantitatively tested in the regressions presented above. The composite willingness index serves as a behavioural intention proxy, and the analysis does not claim to validate TAM's causal pathways.

3.7 Reliability of composite scores

The internal consistency of all multi-item composite scores was evaluated using Cronbach's alpha (α) prior to composite index construction. The reliability coefficients obtained were as follows: perceived improvement in food processing efficiency (4 items, $\alpha = 0.84$), perceived improvement in water supply reliability (4 items, $\alpha = 0.89$), and willingness to adopt agrivoltaics (3 items, $\alpha = 0.81$). All estimated values exceeded the conventionally recommended threshold of $\alpha \geq 0.70$, thereby confirming satisfactory to good levels of internal consistency for each construct. These results indicate that the indicator items within each composite scale demonstrated adequate inter-item coherence, supporting the reliability of the measurement instrument employed in this study.

3.8 Exploratory factor analysis and TAM construct validation

Table 8 presents the factor loadings from the exploratory factor analysis of the 23 perception items. The four-factor solution explained 58.3% of the total variance. Factor 1 (Perceived Usefulness – Food & Water) included items related to agrivoltaics improving water access (loading 0.81), reducing post-harvest losses (0.76), and enabling evening processing (0.73). Factor 2 (Perceived Barriers / Low Ease of Use) included high upfront cost (0.79), fear of theft (0.68), lack of local repair capacity (0.72), and concerns about panel cleaning (0.61). Factor 3 (Land Tenure & Benefit Sharing) included secure rights to farmland (0.74), willingness on communal land (0.69), and equal benefit sharing (0.71). Factor 4 (Social Influence & Facilitating Conditions) included neighbour adoption influence (0.68), community leader influence (0.65), and belief in government/NGO support (0.62). No item cross-loaded above 0.40.

The factor structure supports the application of TAM constructs in this context. The strong loading of cost and technical maintenance items on Factor 2 (Barriers/Low Ease of Use) aligns with TAM's prediction that perceived ease of use (or its inverse, perceived difficulty) influences adoption intention. The emergence of land tenure as a separate factor (Factor 3) suggests that in the Nigerian context, tenure security operates as a distinct external variable not fully captured by standard TAM constructs. Similarly, social influence (Factor 4) emerged as a distinct dimension, consistent with extensions of TAM such as UTAUT. These findings indicate that while perceived usefulness is strongly associated with willingness (OR = 1.42–1.53), perceived barriers; particularly cost and ease-of-use concerns, substantially moderate this relationship.

3.9 Preliminary Economic Feasibility: Levelized Cost of Energy (LCOE) Comparison

Although this study is primarily perceptual, a simplified economic analysis is presented to ground the policy recommendations in local cost realities. The Levelized Cost of Energy (LCOE); the average cost per kilowatt-hour of electricity produced over a system's lifetime, is calculated for a hypothetical agrivoltaic system in Anambra and compared with the cost of diesel generator electricity, which is the predominant alternative for rural food processing and water pumping.

3.9.1 Assumptions and local cost data

A technoeconomic analysis conducted at the National Root Crop Research Institute in Abia State, a geographically proximate state to Anambra, evaluated a 24 kWp solar photovoltaic (PV) system designed for agricultural irrigation purposes [39]. The total capital cost of the system was reported at ₦13,900,000, comprising ₦6,600,000 allocated to solar panels, ₦3,000,000 for a modular inverter configuration, and the remainder distributed across associated balance-of-system infrastructure components. By applying a proportional scaling approach, the estimated capital cost of a smaller 10 kWp system considered appropriate for rural community-level deployment falls within the range of approximately ₦5,800,000–₦7,500,000. This estimate is broadly consistent with findings reported for Nigerian residential hybrid energy systems, wherein a 4 kW PV/battery configuration was found to achieve a levelised cost of energy (LCOE) of \$0.068 kWh^{-1}, equivalent to approximately ₦109 kWh^{-1} at prevailing exchange rates [40]. Collectively, these cost benchmarks suggest that solar PV systems of the scale relevant to agrivoltaic implementation in rural Anambra State are approaching economic viability, particularly when evaluated against the chronic unreliability and escalating operational costs associated with diesel-powered alternatives.

Recent market price data sourced from the Nigerian solar energy retail sector indicate that a 5 kWh battery storage system, inclusive of inverter and a 3 kW solar PV installation, is commercially available at an approximate cost of ₦2,700,000, including installation charges. A larger 10 kWh system paired with a 6 kW PV array is correspondingly priced at approximately ₦6,930,000. For the purposes of the present technoeconomic analysis, a 10 kWh battery bank was assumed as the reference storage configuration, with an estimated procurement and installation cost in the range of ₦5,000,000–₦6,500,000.

Battery storage lifespan represents a critical cost determinant under the hot and humid climatic conditions characteristic of tropical southeastern Nigeria. Conventional lead-acid battery technologies typically necessitate replacement within 2–3 years under such operating conditions, whereas lithium-ion systems demonstrate substantially greater longevity, with a projected operational lifespan of 6–10 years [40]. For the purpose of financial modelling in this study, a conservative mid-case scenario was adopted, assuming the deployment of lithium-ion batteries with a replacement interval of every 8 years over the project evaluation period. This assumption reflects both the superior thermal stability of lithium-ion chemistry relative to lead-acid alternatives and the need to account for performance degradation under sustained high-temperature operating conditions.

Diesel generator cost parameters adopted in this analysis were derived from empirical data reported in hybrid renewable energy studies conducted within the Nigerian context. A technoeconomic study undertaken in Kwara State, Nigeria, employed diesel generator cost assumptions consistent with prevailing Nigerian market conditions [41], while residential hybrid system optimisation research reported diesel generator capital costs in the range of approximately \$500–\$1,000 per kVA [40]. On the basis of these established benchmarks, the capital cost of a 10 kVA diesel generator unit relevant to rural community-scale applications in the study area is estimated at ₦1,200,000–₦1,800,000, inclusive of procurement and installation. This cost range serves as the reference baseline for comparative technoeconomic assessment against solar PV and hybrid agrivoltaic system alternatives considered in the present study.

Fuel cost parameters were derived from official price statistics published by the Nigerian National Bureau of Statistics, which reported an average retail price of ₦1,813.81 per litre of diesel fuel as of June 2025 [42]. Under typical operating conditions, a 10 kVA diesel generator consumes approximately 2–3 litres of fuel per hour at rated load. Assuming a daily operational requirement of 6 hours, consistent with the energy demand profile of rural agro-processing and water pumping applications considered in this study, daily diesel consumption is estimated at approximately 15 litres, corresponding to a daily fuel expenditure of approximately ₦27,200. On an annualised basis, this translates to a fuel cost of approximately ₦9.9 million per year, representing a substantial and recurrent operational burden for rural community energy users. In addition to fuel expenditure, routine generator maintenance costs are estimated at ₦50,000–₦150,000 per month, encompassing scheduled servicing, lubricant replacement, and minor component repairs. When aggregated, the combined fuel and maintenance costs associated with diesel generator operation underscore the significant long-term financial liability of continued dependence on fossil fuel-based energy supply in rural southeastern Nigeria, and provide a relevant economic baseline against which the cost-competitiveness of agrivoltaic system deployment may be assessed.

The economic viability of agrivoltaic systems under West African climatic conditions has been examined in a small but growing body of literature, providing contextually relevant benchmarks for the present study. A profitability assessment conducted in Burkina Faso, a country characterised by solar irradiance and agroecological conditions broadly comparable to those prevailing in Anambra State, southeastern Nigeria, demonstrated that high-density agrivoltaic configurations achieved positive Net Present Values (NPV) ranging from EUR 9,401 to EUR 60,412 at a discount rate of 12% [15]. The authors concluded that agrivoltaic systems are economically viable under West African conditions, while emphasising that financial performance is highly sensitive to system configuration density and the discount rate applied in the analysis. These findings are particularly instructive for the Nigerian context, where comparable solar resource availability, subsistence-oriented farming systems, and constrained access to grid electricity create analogous structural conditions for agrivoltaic adoption. The positive NPV outcomes reported for Burkina Faso suggest that, under appropriate configuration and financing arrangements, agrivoltaic systems in Anambra State may similarly achieve economic viability, thereby reinforcing the relevance of the technoeconomic framework applied in the present analysis.

3.10 LCOE calculation

The LCOE is calculated using the standard formula:

$$LCOE = \frac{\text{Total lifetime costs}}{\text{Total lifetime energy production}} \tag{6}$$

Table 9 presents the LCOE calculation for the proposed solar agrivoltaic system under local Anambra conditions, while Table 10 provides the corresponding LCOE for a diesel generator system of comparable capacity, serving as the baseline for comparison.

Comparison and sensitivity

The solar agrivoltaic LCOE (approximately ₦80/kWh) is substantially lower than the diesel LCOE (approximately ₦736/kWh); a difference of nearly an order of magnitude. This finding is consistent with published Nigerian research. A hybrid renewable energy optimisation study in Kwara State found an LCOE of USD 0.455/kWh (approximately ₦728/kWh at current exchange rates) for a PV/wind/battery/diesel hybrid system. Nigerian residential hybrid system research by [41] reported grid-tied PV/battery LCOE of 0.068/kWh (≈₦109/kWh) and standalone PV/diesel/battery

LCOE of 0.412/kWh (≈₦659/kWh). The Burkina Faso agrivoltaic study further confirms that such systems can achieve positive economic returns in West Africa, with NPV ranging from EUR 9,401 to EUR 164,733 depending on configuration density and discount rate [15].

However, several caveats apply. First, the solar LCOE is sensitive to battery costs and replacement frequency; if lead-acid batteries (3-year replacement cycle) are used instead of lithium-ion (8-year cycle), the LCOE would increase significantly. Second, the diesel LCOE calculation excludes externalities such as noise, air pollution, and carbon emissions. Third, these figures are indicative and should be refined with site-specific data from pilot installations. Fourth, the high upfront capital requirement for solar (₦7–10 million) remains a barrier even if lifetime costs are lower, underscoring the need for blended financing mechanisms (Table 11).

3.11 Discussion of results

The results consistently show that rural stakeholders in Anambra perceive agrivoltaics as a promising solution to their dual energy deficits. The high mean for Item 3 (water access) reflects the daily, visceral experience of water scarcity. This finding aligns with the report by Aliyu et al. [44], which found that solar-powered water pumping systems present the most reliable operational potentials among farmers. The even higher R^2 for the water model (24.1%) suggests that water problems are more universally felt and understood than food processing challenges, which vary by crop and season. The strong positive association between willingness to adopt agrivoltaics and perceived improvements (OR = 1.42 for food processing, OR = 1.53 for water reliability) is encouraging but must be interpreted cautiously. Each one-point increase in the willingness composite score was associated with 42–53% higher odds of reporting greater perceived improvements. However, all findings are based on subjective perceptions, not objective measurements. Respondents' reported agreement that agrivoltaics would reduce losses (mean = 4.2) reflects stated beliefs, which may diverge from actual technical performance. Perceptions are valuable for understanding social acceptability and barriers, but they cannot substitute for engineering or economic validation. Also, this association may be bidirectional: those who perceive greater benefits are more willing to adopt, and those who are more willing may also imagine larger benefits. Moreover, unmeasured variables such as general trust in new technologies or prior positive experiences with solar projects could influence both constructs. Therefore, these odds ratios reflect stated perceptions and should not be interpreted as causal predictions of adoption behaviour. Hence, causality likely runs both ways: positive expectations drive willingness, but willingness also shapes expectations. With this, there is need for a study that features real-time agrivoltaic installations and evaluations.

The land tenure findings reveal a critical but often overlooked dimension of agrivoltaic feasibility. While 58% of respondents reported family-owned land, the remaining 42% operate under communal allocation, rental, or informal arrangements; tenure forms that do not confer long-term investment security. This is consistent with patterns documented across southeastern Nigeria, where customary systems grant use rights but not full ownership, and where land can be reallocated by family heads or village councils [45, 46]. The neutral mean score (2.95) for perceived tenure security over a 10-year horizon underscores this vulnerability.

Agrivoltaic systems typically require 20- to 30-year commitments to recover capital costs; if a farmer or community cannot guarantee land access beyond the next planting season, adoption becomes irrational regardless of technical potential. Notably, respondents were more willing to accept agrivoltaics on communal land with collective decision-making (mean = 4.12) than on family-owned land for private benefit (mean

Table 9. LCOE for the solar agrivoltaic system (10 kWp, 25-year lifespan, average daily energy production of 35 kWh assuming 5 peak sun hours and 70% system efficiency) [39, 43].

Cost Component	Value (₦)	Source
Capital cost (Capex)	7,000,000	Scaled from Abia State 24 kWp system [39]
Annual O&M (₦75,000/year × 25)	1,875,000	Industry standard for tropical conditions
Battery replacement (₦5,500,000 every 8 years × 3 replacements)	16,500,000	Nigerian market prices
Total lifetime cost	25,375,000	
Lifetime energy production (35 kWh/day × 365 days × 25 years)	319,375 kWh	
LCOE (solar)	₦79.5/kWh	

Table 10. LCOE for the diesel generator system (10 kVA, 10-year lifespan, 6 hours daily operation, 70% average load) [40, 41].

Cost Component	Value (₦)	Source
Capital cost	1,500,000	Nigerian market [40]
Annual fuel (₦27,200/day × 365)	9,928,000	NBS diesel price ₦1,814/litre
Annual maintenance (₦100,000/month × 12)	1,200,000	Industry estimate
Total annual operating cost	11,128,000	
Total lifetime cost (10 years): ₦1,500,000 + (₦11,128,000 × 10)	112,780,000	
Lifetime energy production (10 kW × 70% × 6 h × 365 days × 10 years)	153,300 kWh	
LCOE (diesel)	₦735.7/kWh	

= 3.78), suggesting that community-managed models may be more culturally and institutionally appropriate than individual-ownership models. The strong endorsement of equal benefit sharing (mean = 4.34) aligns with the communitarian ethos prevalent in Igbo land tenure systems, where land is often viewed as a community asset rather than a commodity [47]. However, the lower willingness among renters and squatters (mean = 2.56) indicates that these vulnerable groups could be excluded from agrivoltaic benefits unless deliberate inclusive design is implemented. Future pilot projects must therefore negotiate land use agreements through traditional governance structures (e.g., village councils, kindred heads) rather than only with individual landowners, and must embed transparent benefit-sharing rules that address the legitimate claims of non-landowning farmers.

The non-significance of income and occupation in Y1 was unexpected but has reasonable explanations. Income may not matter because even wealthier households still lack grid access and face the same fuel costs; the perceived benefit of agrivoltaics is relative to a universally bad baseline. Occupation (food processor and farmer) may be insignificant because many farmers engage in small-scale processing at home. This finding suggests that agrivoltaic interventions should target whole communities rather than specific occupational groups.

The high agreement on initial installation cost as the main barrier (mean = 4.38) can be interpreted through the Technology Acceptance Model as a trade-off between perceived usefulness and perceived ease of use, moderated by external economic constraints. TAM suggests that even when perceived usefulness is high (as it is here: mean = 4.21–4.53 for usefulness items), adoption may be blocked if the technology is perceived as difficult to acquire or maintain. In this case, the upfront capital requirement (≈₦15–30 million for a 10–20 kW system) is not merely a financial obstacle but fundamentally alters the perceived ease of use: a technology that requires external financing, loan applications, or government approval is perceived as less "easy" to adopt than one that can be purchased with household savings. This finding extends TAM by highlighting that in low-income rural contexts, economic accessibility functions as

Table 11. Summary of simplified LCOE comparison for Anambra context based on Nigerian and West African published data.

Parameter	Solar Agrivoltaic (10 kWp)	Diesel Generator (10 kVA)
Capital cost (₦)	7,000,000 [39]	1,500,000 [40]
Annual O&M (₦)	75,000	11,128,000 (incl. fuel)
Battery replacement (₦)	5,500,000 every 8 years	N/A
Lifespan (years)	25 [39]	10 [40]
Lifetime cost (₦)	25,375,000	112,780,000
Lifetime energy (kWh)	319,375	153,300
LCOE (₦/kWh)	∼80	∼736
West African agrivoltaic NPV reference: EUR 9,401–60,412 [15]		

Note: Diesel LCOE based on NBS diesel price of ₦1,814/litre (June 2025). Solar costs based on Nigerian market data from Abia State and national residential system studies.

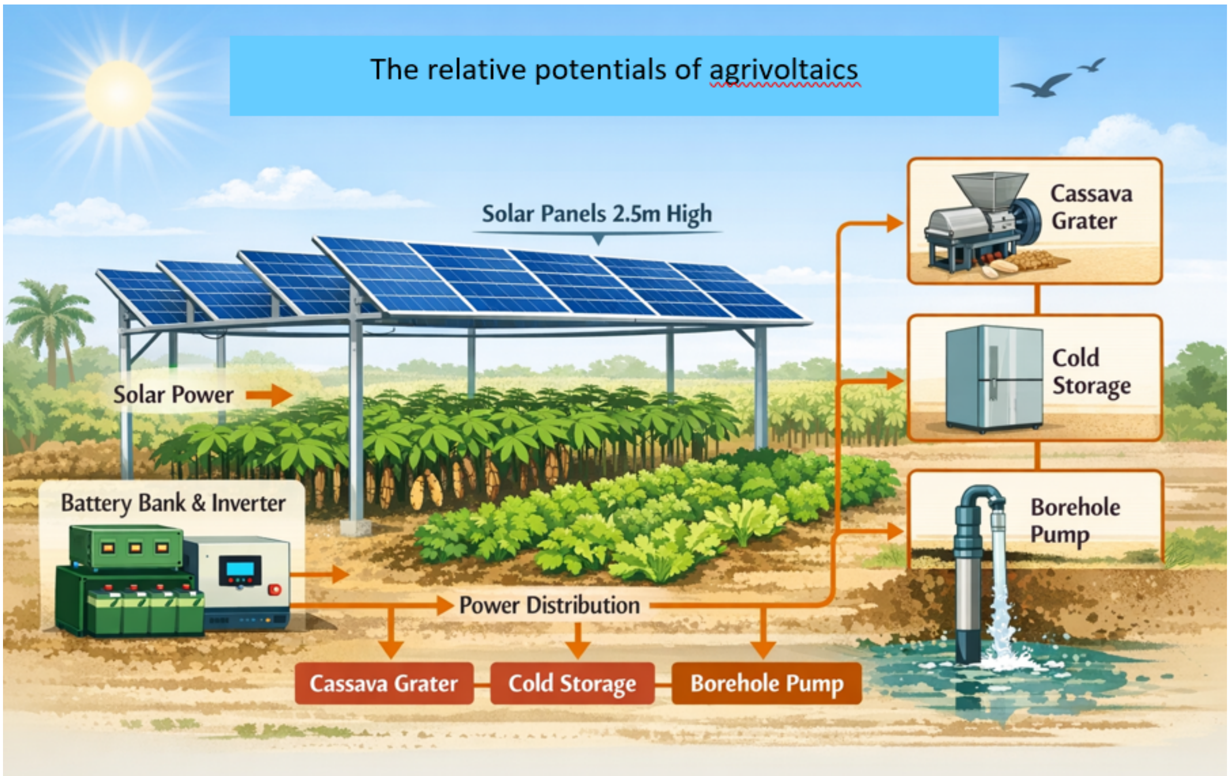

Figure 3. Conceptual diagram of an adaptable agrivoltaic system for Anambra Agricultural Zone (Authors, 2026).

a component of perceived ease of use. This economic reality aligns with findings from Awka South, where Umenzekwe et al. [7] demonstrated that unreliable and expensive power supply (primarily from diesel generators) significantly erodes the growth and profitability of small and medium enterprises, further underscoring that any solution must address both capital costs and operational expenditure to be viable for rural stakeholders. The EFA results support this interpretation, with cost loading strongly (0.79) on the Barriers/Ease factor (Factor 2) rather than loading separately. Future agrivoltaic interventions must therefore address not only technical usefulness but also financial accessibility through innovative financing mechanisms (e.g., pay-as-you-go solar, community-based revolving funds).

The open-ended responses added two other critical barriers: fear of theft (56%) and lack of local repair capacity (63%). These are not merely economic; they are institutional and technical. Amjad et al. [48] and Garcia et al. [49] identified capital cost as one of the primary obstacles to solar cold storage adoption in developing countries. Any agrivoltaic project must include security measures (e.g., lockable enclosures, community policing) and a multi-tier maintenance plan with spare parts supply chains [50, 51].

Comparing with other studies, the potential benefits are substantial. Alharbi et al. [22], Ghasemi and Sadeghkhani [23] and Pandey et al. [52] agreed to the fact that agrivoltaics reduced irrigation water demand by 14–23% due to lower evaporation. In Anambra's higher temperatures, the reduction could be even greater. Similarly, Rutta [53] reported that post-harvest tomato losses in Sub-Saharan Africa can reach 20–50% due to inadequate storage. The introduction of solar-powered cold storage systems has been shown to significantly reduce these losses by extending shelf life up to four times and reducing spoilage rates substantially.

The finding that 83% of respondents currently travel to nearby towns for cassava grating describes existing coping strategies but does not constitute evidence that agrivoltaics would replace these services. Replacement would depend on whether solar powered local processing is cheaper, more convenient, and trusted relative to established diesel mill operators. If similar results were achieved in Anambra, the economic impact could be substantial, but this remains speculative. Respondents' strong agreement that agrivoltaics would reduce losses (mean = 4.2) indicates positive expectations, but actual economic benefits would need to be verified through monitored pilot projects with cost accounting. However, those studies operated in contexts with better infrastructure and existing solar supply chains. The Anambra case lacks even basic inverter repair shops in most rural towns. Thus, while the potential is real, the implementation pathway must be tailored to local institutional realities.

While a simplified LCOE analysis was conducted (Section 3.9), comprehensive financial modelling (NPV, IRR, payback period) was not performed and should be addressed in future feasibility studies using site-specific data. While respondents strongly agreed that high upfront cost is a barrier (mean = 4.38), such calculations would require specific assumptions about system size (e.g., 10–20 kW), local solar irradiance (approximately 4.5–5.5 kWh/m²/day in Anambra), battery degradation rates under humid tropical conditions, and avoided costs of diesel and grid electricity. Future feasibility studies must integrate engineering cost models with the perceptual data presented here.

The conceptualize features of a proposed agrivoltaic system in the Anambra Agricultural Zones context; where solar panels are elevated at 2.5 m above cassava/vegetable crops, with a battery bank, inverter, and connections to a cassava grater, cold storage unit, and borehole pump, is presented as in Figure 3.

3.12 Limitations of the Study

This study has several methodological limitations. The analysis is based on stated perceptions and willingness rather than observed behaviour or measured outcomes; while useful for understanding attitudes, perceptions do not necessarily translate into actual adoption, and stronger evidence would require experimental or quasi-experimental designs with real agrivoltaic installations. The cross-sectional design captures responses at a single point in time, but attitudes toward novel technologies are not static and may shift with changes in grid supply or crop failures. Although sampling was rigorous within Anambra, the findings may not be generalizable to other Nigerian regions due to variations in agro-ecological conditions, cropping systems, and land tenure arrangements. This study assessed perceptions only; claims about agrivoltaics offering a "pathway toward energy and food security" reflect stakeholder beliefs, not demonstrated performance; actual energy output and loss reduction would require monitored pilot installations. No economic analysis (ROI, LCOE, NPV) was conducted; statements about "transformative economic impact" are speculative and reflect stakeholder expectations, not validated projections. While gender data were collected, gender was not included as an independent variable in regression models due to sample size constraints, meaning gender-specific conclusions cannot be drawn from the quantitative analysis.

The regression models are associational, not causal. Two endogeneity concerns are salient: reverse causality (those who perceive greater benefits are more willing to adopt, creating bidirectional association) and omitted variable bias (unmeasured factors such as general trust in technology, community leadership, prior solar exposure, risk tolerance, and social capital may influence both willingness and perceived improvements). No valid instrumental variable was available (first-stage F = 4.2), so readers should interpret OR = 1.42 and 1.53 as reflecting stated perceptions shaped by unobserved heterogeneity. Sampling frame coverage bias exists: the frame included only ADP-registered farmers (~20,056), excluding many rural farmers, particularly women and youth. The study was conducted exclusively in Anambra's tropical rainforest zone; findings may not generalize to semi-arid or Sahelian zones (e.g., Sokoto, Borno), coastal or mangrove zones, or urban areas. No objective performance data were collected; all outcomes are subjective Likert perceptions, which are susceptible to mood, recency effects, and social desirability bias. While cross-validation with categorical questions provided reassurance, it does not replace objective measurement. Theoretical validation is exploratory, not confirmatory; the EFA revealed a four-factor structure consistent with TAM, but confirmatory factor analysis on an independent sample is needed, and future research should use validated TAM or UTAUT instruments with structural equation modelling.

4 Conclusion

This case study of Anambra's humid tropical zone (findings not directly generalizable) assessed whether agrivoltaics could address food processing and water supply challenges. Evidence from 840 farmers, processors, and water users indicates agrivoltaics are promising but with caveats. Respondents overwhelmingly agreed that current electricity access is grossly inadequate (3.2 hours/day for the few connected), causing substantial post-harvest losses and water scarcity, while broadly agreeing that elevated solar panels could provide reliable power without sacrificing farmland—strongest agreement was for water supply improvements.

Willingness to contribute labour or modest fees for community-managed systems was present among a majority, though a significant minority expressed skepticism. Ordinal logistic regression showed willingness to adopt agrivoltaics was significantly associated with higher perceived improvements in food processing (OR = 1.42, $p < 0.01$) and water supply (OR = 1.53, $p < 0.01$), but these associations reflect stated perceptions, may be bidirectional, and causality cannot be established from this cross-sectional design. High upfront cost is universally recognized as the primary barrier.

Agrivoltaics is not a magic bullet; it requires upfront capital, technical expertise, ongoing maintenance, community governance to prevent elite capture, and secure land tenure for 20-30 year lifespans, but the alternative (diesel generators, kerosene, manual water hauling) is unsustainable. Based on stakeholder perceptions, agrivoltaics appear promising, but this promise must be validated through pilot installations with measured outcomes. Future comparative research across Nigeria's agro-ecological zones (Sahel, Sudan savanna, Guinea savanna, rainforest, mangrove) is needed. The qualitative observation that women are heavily involved in post-harvest processing is illustrative, but this study did not quantitatively test gender differences in adoption willingness; future research should include gender-disaggregated analyses.

5 Recommendations

Based on the study findings, the following recommendations are proposed for policymakers, development agencies, and community-based organizations:

- Establish pilot agrivoltaic demonstration sites in high-willingness communities, scaled to local energy needs (e.g., borehole pump and small processing mill) with panels elevated for continued crop cultivation. Exact configurations require engineering assessment of local solar irradiance (4.5–5.5 kWh/m^2/day) and specific load requirements.
- Design agrivoltaic systems as integrated service hubs (cassava graters, rice mills, cold storage, borehole pumps) so communities experience immediate benefits. Equipment prioritization should be informed by community consultations and local value chain analysis.
- Introduce blended financing with public/donor funding as the primary share, complemented by community contributions (labour, land, or low-interest micro-loans). The exact ratio requires context-specific financial modelling using LCOE analysis.
- Strengthen local technical skills by training technicians on solar maintenance, battery care, inverter troubleshooting, and electrical safety through nearby technical institutions.
- Establish transparent community management structures with gender and age representation, shared financial oversight, and regular public updates on income and expenses.
- Align agrivoltaic initiatives with existing agricultural extension and rural electrification programs to guide farmers on effective system use, including suitable crops for partially shaded conditions.
- Advocate for formal policy recognition of agrivoltaics as a dual-use land approach within national energy and agricultural development plans.
- Prior to large-scale implementation, commission techno-economic assessments (NPV, IRR, payback period, LCOE) incorporating local solar irradiance, battery degradation rates (2–3 years for lead-acid), and avoided diesel costs. Pilot projects must include systematic cost data collection (capital expenditure, O&M, avoided diesel costs, battery replacement cycles) to enable refined economic modelling.
- Future research should: (a) move beyond cross-sectional surveys to longitudinal or quasi-experimental designs (e.g., difference-in-differences) to disentangle reverse causality; (b) replicate the survey instrument across semi-arid, Sudan savanna, Guinea savanna, and mangrove zones to assess regional variability; (c) incorporate mixed methods with household logbooks, weighed post-harvest loss assessments, direct solar performance measurements, and cross-validation with categorical recall questions; and (d) include gender-disaggregated analyses given women's different land rights and energy needs.
- Support long-term (two-year) comparative studies of communities with and without agrivoltaic systems, focusing on post-harvest

losses, water access, energy use, and income changes.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Ethical approval for this study was obtained from the Research Ethics Committee of the Department of Agricultural and Bioresources Engineering, Nnamdi Azikiwe University, Awka (Approval No. ABE/NAU/2025/ETH/002, dated 10 January 2026). Permission was also obtained from the traditional rulers of all 16 sampled communities to respect local governance structures. All participants provided verbal informed consent after being briefed on the study's purpose, voluntary nature, confidentiality, and their right to withdraw at any time without penalty. No personal identifiers were collected.

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