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# Agrivoltaics for Irrigation Sustainability: A Case Study of Aguata Agricultural Zone, in Anambra State, Nigeria

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**Abstract**
Agrivoltaics offers an integrated solution to water scarcity, energy poverty, and agricultural intensification within the water-energy-food nexus. This study assessed agrivoltaic potential for improving irrigation sustainability in Aguata Agricultural Zone, Anambra State, Nigeria. A cross-sectional survey of 376 agricultural stakeholders, selected through stratified random sampling, evaluated current irrigation practices, awareness, adoption willingness, and perceived importance of agrivoltaics. Results revealed heavy dependence on rain-fed farming (82%), high vulnerability to seasonal water shortages, and critically low awareness of agrivoltaics (79%). Despite this gap, respondents demonstrated strong acceptance, with 84% acknowledging its importance for irrigation sustainability and 86.7% willing to adopt if supported. Inferential analysis revealed significant associations between educational attainment and willingness to adopt ($\chi^2=18.64$, $p<0.01$), farming experience and willingness to adopt ($\chi^2=14.27$, $p<0.05$), and occupation type and perceived importance ($\chi^2=16.91$, $p<0.01$). Correlation analysis showed positive relationships between awareness and willingness to adopt ($r=0.31$, $p<0.01$), while logistic regression identified tertiary education ($OR=3.46$, $p<0.01$), farming experience ($OR=1.06$, $p<0.05$), and awareness ($OR=4.14$, $p<0.01$) as significant predictors of adoption willingness. Key barriers included high capital costs, limited technical capacity, and land tenure constraints. The study concludes that agrivoltaics can enhance irrigation sustainability by providing renewable energy for water pumping, moderating microclimates, and improving land and water productivity. Findings underscore the need for targeted awareness campaigns, pilot projects, enabling policies, financial incentives, and capacity building to facilitate adoption in smallholder farming systems.

**Keywords:** Agrivoltaics, irrigation sustainability, solar energy, sustainable agriculture, Aguata

## 1. Introduction

Global agricultural systems are under unprecedented strain from climate change, population growth, and resource depletion. Among the most critical pressures is the increasing scarcity of freshwater, which threatens irrigation-dependent food production (FAO, 2020). Concurrently, the imperative for a transition to renewable energy to mitigate climate change has spurred a rapid expansion of solar photovoltaic (PV) infrastructure, often leading to competition for finite land resources (Adeh *et al.*, 2019; Anyene *et al.*, 2025). This competition is particularly acute in regions like sub-Saharan Africa, where both food security and energy access are paramount development priorities. Nigeria exemplifies these dual challenges. Agriculture remains a cornerstone of the economy and livelihood for millions, yet it is predominantly rain-fed and highly vulnerable to climatic variability (National Bureau of Statistics, 2023). Irrigation, a key to intensification and resilience, is hampered by erratic electricity supply and the high cost of fossil-fuel-powered pumps, limiting its adoption and sustainability (Udo, 2020). In this context, agrivoltaics emerges as a transformative integrated solution. Defined as the simultaneous use of land for agricultural production and solar PV electricity generation (DIN, 2021), the technology offers a pathway to reconcile land-use conflicts while delivering mutual benefits across the food-energy-water nexus (Barron-Gafford *et al.*, 2019).

The theoretical premise of agrivoltaics for irrigation sustainability is multifaceted. First, the physical infrastructure of elevated solar panels creates a moderated microclimate underneath. Shading reduces soil temperature and plant exposure to direct solar radiation, thereby lowering evapotranspiration rates and conserving soil moisture. Studies in arid regions have demonstrated significant reductions in irrigation water requirements for crops grown under PV arrays

(Barron-Gafford *et al.*, 2019; Elamri *et al.*, 2018). Secondly, the electricity generated on-site can directly power irrigation pumps, providing a reliable, clean, and cost-effective alternative to diesel or grid-dependent systems. This solar-powered irrigation (SPI) enhances energy autonomy for farmers and reduces operational costs and carbon emissions (Khatri *et al.*, 2022). Thirdly, by combining two land uses, agrivoltaics increases land equivalent ratios (LER), achieving greater total productivity per unit area than separate systems for food and energy (Trommsdorff *et al.*, 2022).

Despite its documented potential in temperate and arid developed regions, the application and perception of agrivoltaics in tropical African agricultural systems, particularly concerning irrigation, remain underexplored. While countries like Germany, Japan, and France have established pilot projects and regulatory frameworks, implementation in Nigeria is nascent, with awareness and technical expertise identified as major barriers (Babarinde, 2024; IISD, 2023). Addressing irrigation sustainability is critical for food security, climate adaptation, and rural economic development in Nigeria. This research is significant for several reasons. Practically, it provides evidence-based insights for policymakers, agricultural extension services, and development agencies on the opportunities and barriers to deploying agrivoltaics in a typical Nigerian agricultural zone. Theoretically, it contributes to the growing literature on the water-energy-food nexus by applying the agrivoltaics concept in a new socio-ecological context. Technologically, it highlights the need for context-appropriate designs and business models for tropical smallholder farming systems. The findings can inform the design of pilot projects, subsidy schemes, and training programs to facilitate the transition towards more resilient and productive agricultural systems.

This study focuses on the Aguata Agricultural Zone in Anambra State, south-eastern Nigeria. The area was selected as a critical case study due to its representative vulnerability: it embodies a high-dependence on rain-fed cultivation within a tropical climate with prolonged dry seasons, yet suffers from a lack of efficient and affordable irrigation infrastructure (Anyadiuno and Chukwuka, 2021). The reliance on inefficient manual methods or costly fuel-powered pumps during dry periods makes it a pertinent site for investigating sustainable irrigation solutions (Xie *et al.*, 2017). This research, therefore, seeks to bridge the knowledge gap by empirically assessing the local context for agrivoltaics adoption. It does not aim to present primary experimental data on crop yields or hydrological measurements under agrivoltaic systems but rather to evaluate the socio-technical landscape: the current state of irrigation, the level of awareness and application of agrivoltaics, farmers' perceptions of its importance, and their willingness to adopt it.

Employing a cross-sectional survey design, this study evaluated the potential of agrivoltaic systems to improve irrigation sustainability in the Aguata Agricultural Zone. The specific objectives were to:

i. assess the level of awareness and perceived application of agrivoltaic systems among agricultural stakeholders in the Aguata Agricultural Zone;
ii. ascertain the willingness of farmers and agricultural stakeholders to adopt agrivoltaics and identify the perceived barriers to its integration into the agricultural framework of the zone; and
iii. evaluate the perceived importance of agrivoltaics in promoting irrigation sustainability within the zone.

## 2.0 Literature Review

### 2.1 Agrivoltaics and the water–energy–food nexus in developing regions

Agrivoltaics refers to the dual use of land for agricultural production and solar photovoltaic (PV) electricity generation. This integrated land-use system is increasingly relevant for developing regions facing interlinked water, energy, and food security challenges (DIN, 2021). Unlike conventional solar farms that displace farming activities, agrivoltaic systems allow crops to grow beneath or between PV panel arrays, thereby improving land-use efficiency and enabling simultaneous food and energy production (Rahman *et al.*, 2023).

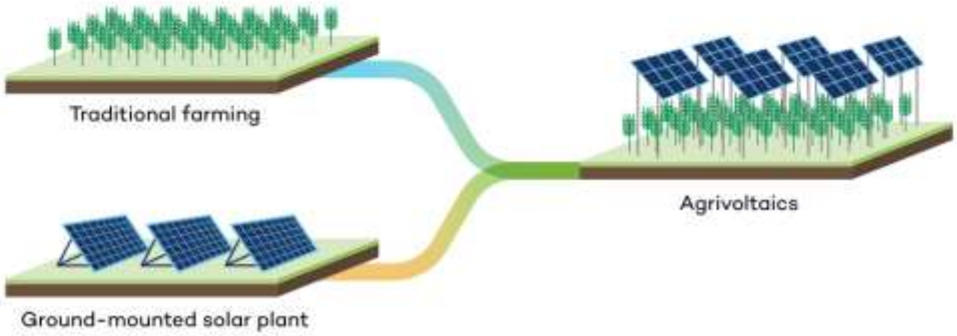

**Figure 1: A typical agrivoltaics system showing crop cultivation beneath elevated solar panels (Rahman *et al.*, 2023).**

The concept aligns with the water–energy–food (WEF) nexus, which emphasizes the interdependence of water, energy, and food systems. In sub-Saharan Africa, where agriculture is predominantly rain-fed and rural energy access is limited, these linkages are particularly significant (Falchetta *et al.*, 2023). Agrivoltaic systems address these challenges by generating solar electricity for irrigation while creating microclimatic conditions that reduce evapotranspiration and potentially improve PV efficiency through crop-induced cooling (Anyene *et al.*, 2025; Barron-Gafford *et al.*, 2019).

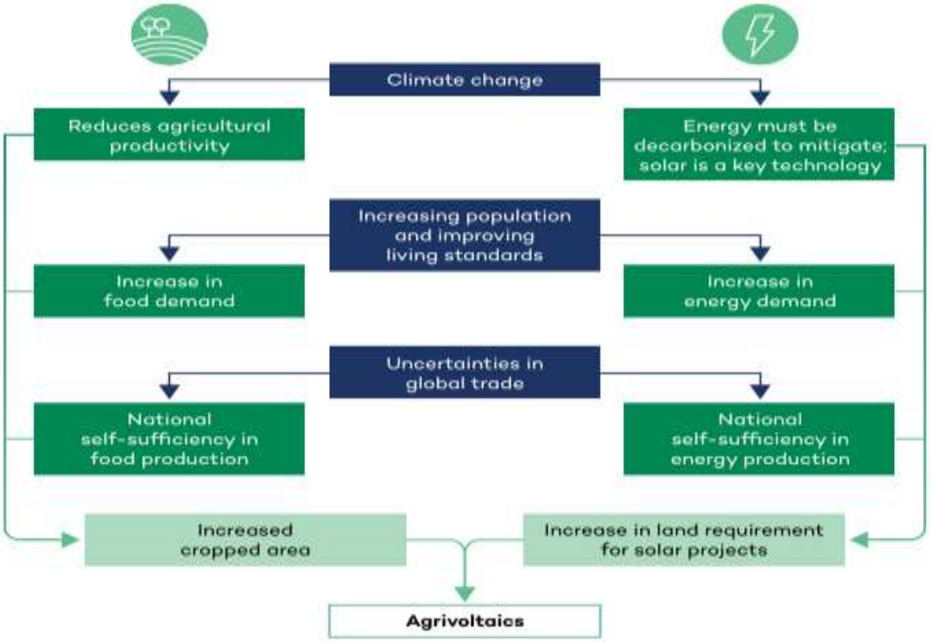

**Figure 2: Agrivoltaics as a food–energy nexus approach to resource use (Rahman *et al.*, 2023).**

## 2.2 Evidence from tropical and developing regions

Although agrivoltaics research initially focused on temperate developed countries such as Germany, France, and Japan, studies from tropical and semi-arid regions demonstrate its relevance for developing economies. In water-limited environments, PV shading can improve soil moisture retention and reduce irrigation demand. Barron-Gafford *et al.* (2019) found significantly higher soil moisture beneath PV panels in dryland regions of the south-western United States, reducing irrigation frequency. Similarly, Elamri *et al.* (2018) reported that vegetable crops under agrivoltaic conditions maintained or increased yields while using up to 20% less irrigation water.

In sub-Saharan Africa, solar-powered irrigation systems (SPIS) are increasingly promoted to address unreliable electricity supply and dependence on diesel pumps. Falchetta *et al.* (2023) noted that declining PV costs are improving the economic viability of SPIS for smallholder farmers. However, integration of SPIS within agrivoltaic systems remains largely unexplored in African agriculture. Evidence from India provides useful parallels for Nigeria. Rahman *et al.* (2023) identified farmer acceptance, appropriate system design, and supportive policy frameworks as key determinants for agrivoltaic adoption.

## 2.3 Mechanisms linking agrivoltaics to irrigation sustainability

Agrivoltaics supports irrigation sustainability through several mechanisms. They include:

i. **Microclimate regulation:** Partial shading lowers soil and air temperatures, reducing evapotranspiration and crop water stress, particularly for heat-sensitive crops such as vegetables (Semeraro *et al.*, 2024; Pandey *et al.*, 2025).
ii. **Renewable energy for irrigation:** On-site PV electricity can power irrigation pumps, reducing reliance on diesel or unreliable grid electricity while supporting efficient irrigation technologies such as drip systems (Khatri *et al.*, 2022).
iii. **Resource-use synergy:** Crop transpiration beneath panels cools PV modules, improving electricity generation efficiency, which can increase output by up to 10% in some systems (Othman *et al.*, 2016). Rainwater harvesting from panel surfaces may also supplement irrigation.
iv. **Improved crop-water productivity:** Moderated microclimates and reduced water demand can increase crop yield per unit of water used, with studies reporting improved productivity for crops such as potatoes and vegetables (Witwit *et al.*, 2025; Semeraro *et al.*, 2024).

## 2.4 Design considerations for smallholder systems

Agrivoltaic system design must align with local farming practices and crop requirements. Trommsdorff *et al.* (2022) classified systems based on structural configuration and agricultural use (Figure 3).

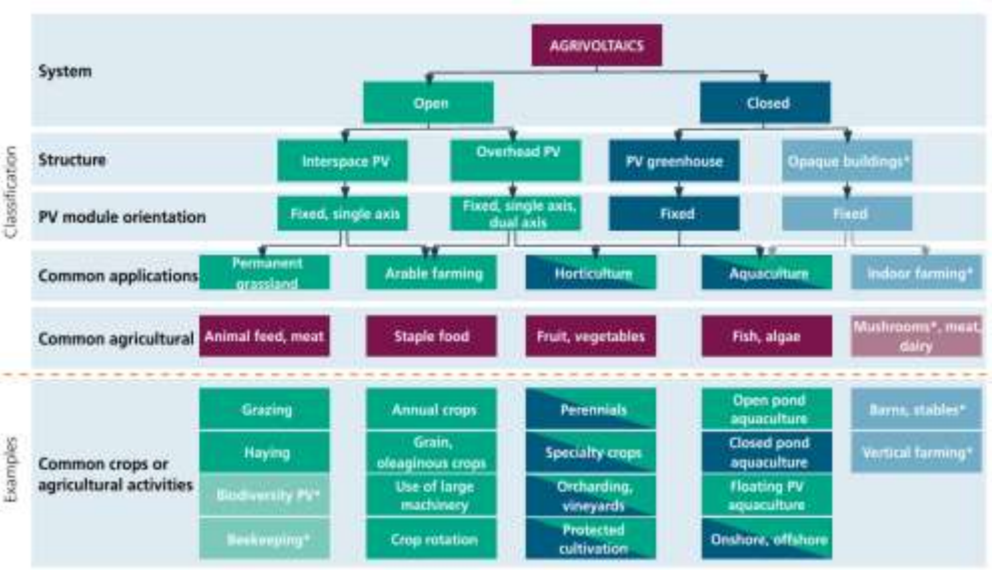

**Figure 3: Classification framework for agrivoltaic systems (Trommsdorff *et al.*, 2022).**

Two configurations are particularly relevant for smallholder agriculture. They are typically developed into:

i. **Overhead or stilt-mounted systems:** Panels elevated 2–4 m above ground allow crop cultivation underneath and support manual farming, though structural costs are higher.
ii. **Interspace systems:** Ground-mounted panels with crops planted between rows reduce installation costs but limit cultivable land area.

Furthermore, Emerging technologies such as vertically mounted bifacial panels and semi-transparent PV materials integrated into greenhouses expand design possibilities but remain capital-intensive for smallholder farmers (Kim & Kim, 2023).

## 2.5 Adoption determinants in developing agriculture

Adoption of agricultural innovations depends on economic, social, and institutional factors. Ominikari *et al.* (2017) found that perceived benefits, compatibility with existing practices, and visible outcomes influence farmer participation in agricultural programs in Nigeria. Tesfaye and Gutema (2022) similarly highlighted awareness, technical support, and access to inputs as key determinants of technology adoption. For agrivoltaics, Babarinde (2024) identified limited awareness and technical capacity as major barriers in Nigeria. The International Institute for Sustainable Development (IISD, 2023) also noted that existing land-use policies often separate agricultural and energy uses, creating regulatory uncertainty for dual-use agrivoltaic systems.

### 2.6 Nigerian context: Opportunities and knowledge gaps

Nigeria has substantial solar energy potential, with average solar irradiance ranging from 4.0–6.5 kWh/m²/day across much of the country (NiMet, 2026). This provides favourable conditions for agrivoltaic deployment, which aligns with national priorities such as renewable energy expansion, agricultural productivity improvement, and climate adaptation (Walston *et al.*, 2022). However, key knowledge gaps remain. Empirical studies on crop responses to agrivoltaic systems for Nigerian staples such as cassava, maize, and yam are limited. There is also little evidence on farmers' awareness, perceptions, and willingness to adopt the technology. Furthermore, institutional support mechanisms; including extension services, financing models, and policy frameworks, are still underdeveloped.

## 3.0 Materials and Methods

### 3.1 Research design and study area

This study employed a cross-sectional survey design combining quantitative and limited qualitative approaches to examine awareness, perceptions, and current practices related to irrigation and agrivoltaic systems. The cross-sectional design was considered appropriate because it allows data to be collected from a defined population at a single point in time in order to describe prevailing conditions and stakeholder perspectives.

The study was conducted in the Aguata Agricultural Zone of Anambra State, located in south-eastern Nigeria (Figure 4). The zone comprises five Local Government Areas (LGAs): Aguata, Orumba North, Orumba South, Nnewi North, and Nnewi South. The area experiences a tropical climate characterized by a bimodal seasonal pattern consisting of a wet season (April–October) and a dry season (November–March). Rain-fed agriculture predominates during the wet season, while irrigation becomes essential for crop production during the dry season. Major crops cultivated in the area include rice, maize, cassava, and other staple food crops. These climatic and agricultural conditions make the zone suitable for examining irrigation practices and potential climate-adaptive innovations such as agrivoltaic systems.

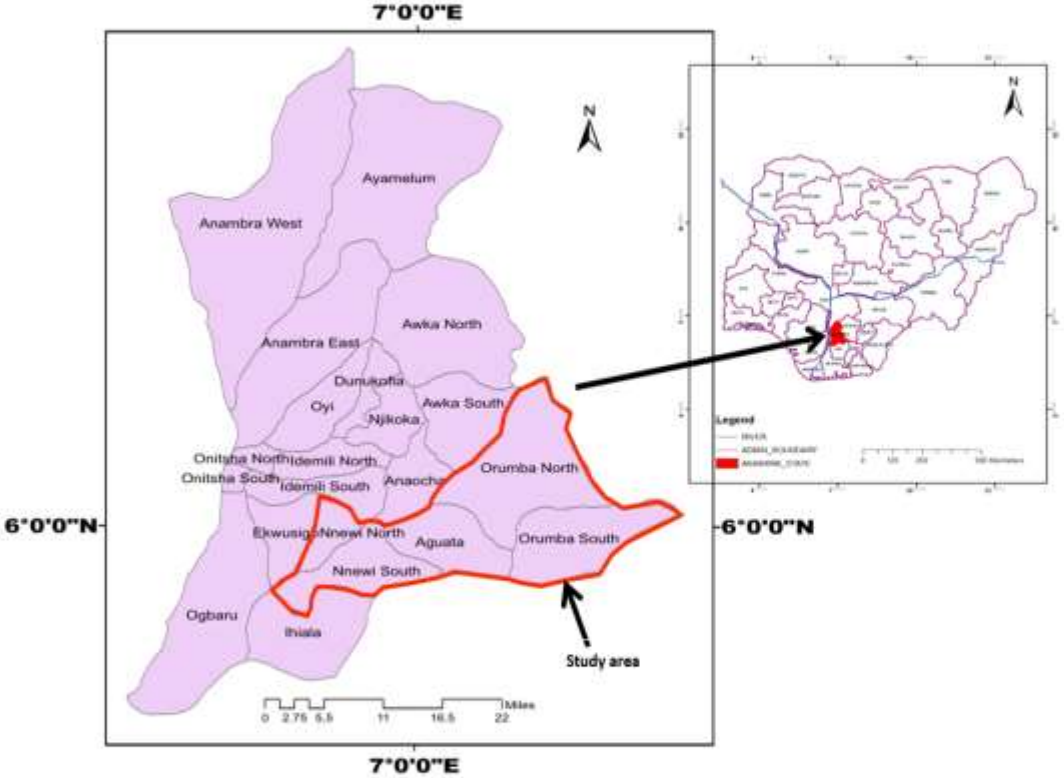

Figure 4: Map of the study area showing the Aguata Agricultural Zone in Anambra State, Nigeria

## 3.2 Target population and sampling strategy

The target population consisted of agricultural stakeholders operating within the Aguata Agricultural Zone. These stakeholders included crop farmers (small-, medium-, and large-scale producers), agricultural extension officers, and community-level water resource managers involved in irrigation activities. These groups were selected because they are directly involved in agricultural production and irrigation management within the study area.

A precise count of all relevant stakeholders in the zone was not available from official census records. Therefore, an approximate population size was established through a multi-stage estimation process. Population projections based on the 2006 National Population Census estimated the combined population of the five LGAs at approximately 855,287 inhabitants as of 2022 (National Population Commission [NPC], 2006; as projected by Anambra State Bureau of Statistics, 2022). To approximate the number of individuals engaged in agriculture, the regional agricultural labour participation rate of approximately 55% reported by national statistical sources was considered. Additional information obtained from the Anambra State Ministry of Agriculture regarding registered farmers and extension personnel within the zone was also incorporated. Based on these sources, the population of relevant agricultural stakeholders was conservatively estimated at approximately 100,000 individuals.

The sample size was determined using Yamane's formula for sample size calculation for large populations (Adams, 2020):

$$n = \frac{N}{1+N(e)^2} \tag{1}$$

Where: n = required sample size
N = estimated population size
e = acceptable sampling error (0.05)

$$\therefore n = \frac{100,000}{1+100000(0.05)^2} = \frac{100,000}{1+100,000(0.0025)} = \frac{100,000}{1+250} = \frac{100,000}{251} = 398.4$$

Using a population estimate of 100,000 and a 5% margin of error, the calculated sample size was approximately 398 respondents. For operational convenience, this figure was rounded to 400 respondents.

A stratified random sampling technique was applied to ensure representation across the five LGAs and the different stakeholder categories. Within each stratum, respondents were selected using systematic random sampling based on available community lists, farmer association registers, and extension service records.

### 3.2.1 Population estimation constraints and methodological considerations

The estimation of the stakeholder population relied on secondary data and therefore involves certain limitations. First, the agricultural labour participation rate used in the estimation reflects regional averages and may not precisely represent the specific agricultural engagement patterns within the Aguata Agricultural Zone. Second, population projections derived from the 2006 census incorporate assumptions regarding demographic growth and migration that may not fully capture localized changes over time. Third, official registers of farmers may not include all active producers, particularly smallholder farmers operating outside formal registration systems.

Despite these limitations, several measures were adopted to improve methodological reliability. Multiple data sources; including census projections, labour statistics, and administrative records, were combined to obtain a more realistic population estimate. The sample size was also calculated conservatively to ensure adequate statistical representation. Furthermore, stratified sampling ensured that respondents from different LGAs and stakeholder groups were included in the study. Given that the primary objective of the study is descriptive; focusing on awareness, perceptions, and current irrigation practices, the selected sample size remains adequate for the statistical analyses performed. The achieved response rate further strengthens the reliability of the dataset.

## 3.3 Data collection instrument and procedure

Primary data were collected using a semi-structured questionnaire designed to capture information relevant to the study objectives. The questionnaire was reviewed by experts in agricultural engineering and rural development to ensure content validity. A pilot test involving 20 respondents from communities outside the main study sample was conducted to assess clarity, relevance, and reliability of the instrument. Necessary adjustments were made based on the feedback obtained. The questionnaire consisted of six sections namely:

A. Socio-demographic characteristics of respondents
B. Current irrigation practices and associated challenges

C. Awareness and knowledge of agrivoltaic technology
D. Existing exposure to or application of agrivoltaic systems
E. Willingness to adopt agrivoltaic technologies
F. Perceived importance of agrivoltaic systems for irrigation sustainability

A total of 400 questionnaires were distributed across the five LGAs with the assistance of trained field enumerators. Of these, 376 questionnaires were completed correctly and returned, resulting in a response rate of 94%.

### 3.4 Data analysis

Data obtained from the questionnaires were coded and analysed using descriptive and inferential statistical methods. Frequencies, percentages, and cross-tabulations were generated to summarize respondent characteristics, irrigation practices, awareness levels, and attitudes toward agrivoltaic systems.

To address the reviewer's concern regarding the need for inferential analysis, the following statistical tests were employed:

i. Chi-square tests of independence were conducted to examine associations between categorical variables, specifically:
    a. Educational attainment and willingness to adopt agrivoltaics
    b. Farming experience and willingness to adopt agrivoltaics
    c. Age category and awareness of agrivoltaics
    d. Occupation type and perceived importance of agrivoltaics for irrigation sustainability
ii. Pearson's correlation analysis was performed to assess the strength and direction of relationships between selected continuous and ordinal variables, including years of farming experience, educational level, age, awareness, and willingness to adopt.
iii. Binary logistic regression analysis was employed to identify the significant predictors of willingness to adopt agrivoltaics, with educational level, farming experience, awareness, and occupation type entered as independent variables.

All statistical analyses were conducted using SPSS (Version 27). A significance level of $p < 0.05$ was used for all tests. The results were presented using tables and charts to facilitate interpretation and comparison across stakeholder groups.

## 4.0 Results

### 4.1 Descriptive statistics results

#### 4.1.1 Demographic characteristics of respondents

Of the 376 respondents surveyed, 71.01% were male, while 28.99% were female. A majority of respondents (71.01%) were within the economically active age bracket of 36–55 years. With respect to occupation, 39.89% were full-time farmers, while 47.87% were part-time farmers. Educational attainment among respondents was relatively high, with 48.94% possessing tertiary education and 22.87% secondary education. In terms of farming experience, 46.01% had between 6–10 years of experience, while 34.04% had ≤5 years of experience.

**Table 1: Respondents' background information (n = 376)**

| Variable | Category | Frequency | Percentage |
|---|---|---|---|
| Gender | Male | 267 | 71.01 |
| | Female | 109 | 28.99 |
| Age | ≤ 25 years | 22 | 5.85 |
| | 26 – 35 years | 34 | 9.04 |
| | 36 – 45 years | 132 | 35.11 |
| | 46 – 55 years | 135 | 35.90 |
| | > 55 years | 53 | 14.10 |
| Occupation | Full-time farmer | 150 | 39.89 |
| | Part-time farmer | 180 | 47.87 |
| | Agric extension officer | 26 | 6.91 |
| | Researcher | 20 | 5.33 |

| | | | |
|---|---|---|---|
| Educational qualification | Primary | 64 | 17.02 |
| | Secondary | 86 | 22.87 |
| | Tertiary | 184 | 48.94 |
| | Vocational/technical | 42 | 11.17 |
| Years of farming experience | ≤ 5 years | 128 | 34.04 |
| | 6 – 10 years | 173 | 46.01 |
| | 11 – 20 years | 64 | 17.02 |
| | > 20 years | 11 | 2.93 |

### 4.1.2 Current irrigation practices and challenges

The survey revealed a heavy dependence on rain-fed agriculture, with 82% of respondents indicating it as their primary mode of cultivation. Only 18% practiced any form of irrigation, of which 13% relied on manual watering methods such as watering cans, while 5% used mechanized irrigation systems, including drip or sprinkler irrigation (Figure 5).

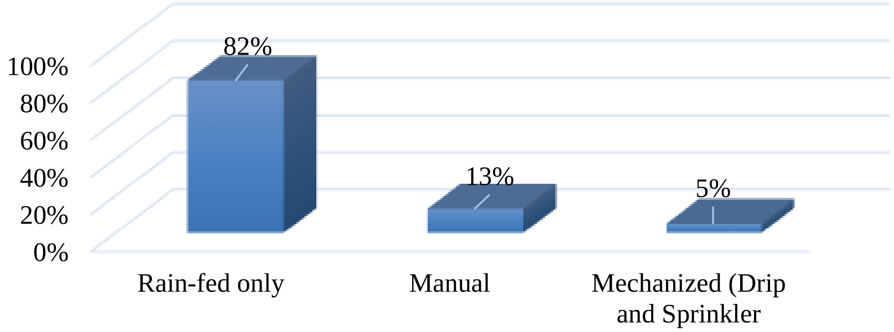

**Figure 5: The irrigation methods that are used in Aguata Agricultural Zone**

Water scarcity was widely reported, with over 85% of respondents experiencing frequent or occasional water shortages during farming seasons, particularly during the dry period. The main water sources used for irrigation included boreholes, rivers, and streams. Respondents also identified high diesel costs for water pumping and limited access to electricity as major constraints to expanding irrigation practices.

### 4.1.3 Awareness and level of application of agrivoltaics

A major finding of the study was the low awareness of agrivoltaic technology among respondents. Approximately 79% indicated that they had never heard of agrivoltaics, while only 21% reported some level of awareness (Figure 6).

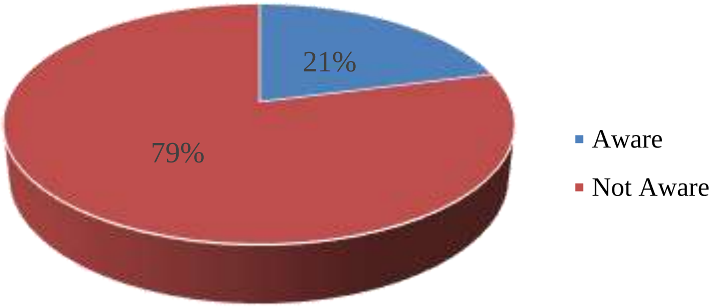

**Figure 6: Awareness of agrivoltaics technology in Aguata Agricultural Zone**

Application of agrivoltaics within the study area was found to be minimal. Only 6.65% of respondents reported that agrivoltaic systems were currently in use on their farms or within their communities, while 73.40% disagreed with this statement (Table 2).

**Table 2: Perception of agrivoltaic applications in Aguata Agricultural Zone (n = 376)**

| Item | SA | A | N | D | SD | % Agree | % Disagree |
|---|---|---|---|---|---|---|---|
| Agrivoltaic systems are currently in use on your farm or within your community | 7 | 18 | 1 | 190 | 86 | 6.65 | 73.40 |
| Positive attitude is maintained by farmers towards adoption | 37 | 179 | 59 | 21 | 21 | 57.45 | 11.17 |
| Agrivoltaics applied in high-scale agriculture | 21 | 23 | 113 | 127 | 92 | 11.70 | 58.24 |
| Agrivoltaics applied in low-scale agriculture | 32 | 47 | 98 | 132 | 67 | 21.01 | 52.93 |
| Agrivoltaics has not gained noticeable application | 54 | 209 | 67 | 25 | 21 | 69.95 | 12.23 |

### 4.1.4 Willingness to adopt agrivoltaics

After respondents were provided with an explanation of agrivoltaic systems and their potential benefits, 86.7% indicated that farmers in the zone would be willing to adopt the technology, while 13.3% indicated unwillingness (Figure 7).

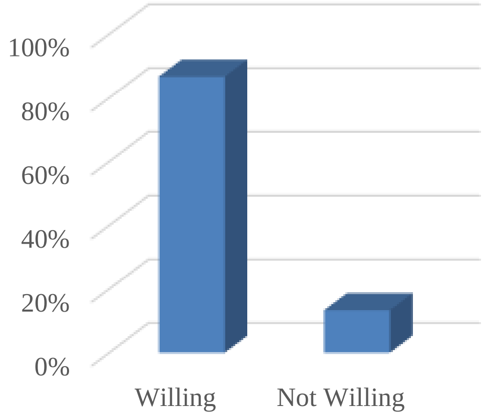

**Figure 6:** Stakeholder willingness to adopt agrivoltaics in Aguata Agricultural Zone

Respondents also identified several major barriers to adoption, including high installation cost, lack of knowledge about the technology, land scarcity and maintenance requirements (Figure 8).

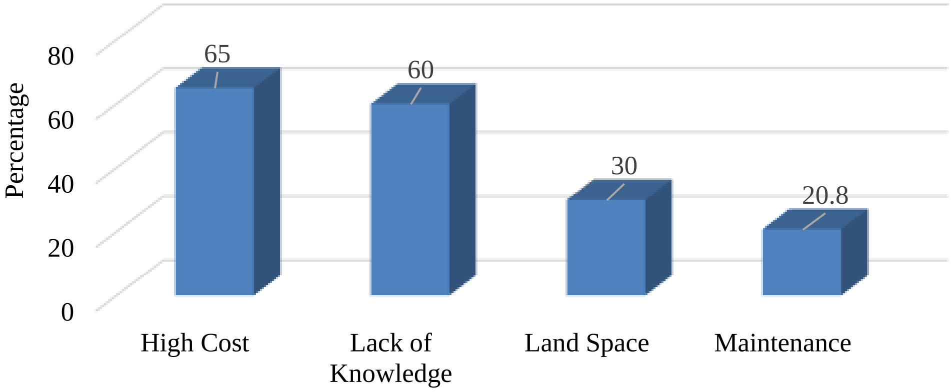

**Figure 8:** Perceived barriers to agrivoltaics adoption

### 4.1.5 Perceived importance for irrigation sustainability

When respondents were asked about the importance of agrivoltaics for irrigation sustainability, 84% indicated that the technology was very important, while 16% perceived it as not important (Figure 9). Respondents associated agrivoltaics with potential benefits such as improved irrigation reliability, reduced water use, lower irrigation costs, continuous water supply, and improved environmental sustainability.

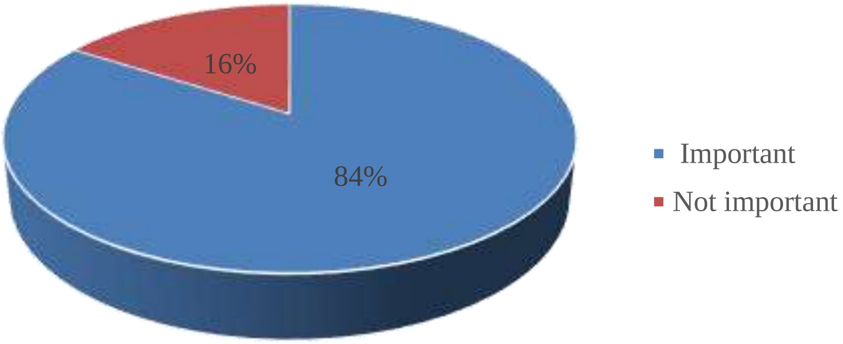

**Figure 9: Perceived importance of agrivoltaics for irrigation sustainability**

## 4.2 Inferential statistical analysis

### 4.2.1 Association between educational attainment and willingness to adopt agrivoltaics

A chi-square test of independence was conducted to examine the relationship between educational level and willingness to adopt agrivoltaic technology. The results revealed a statistically significant association between these variables ($\chi^2 = 18.64$, df = 6, $p < 0.01$), as shown in Table 3.

**Table 3: Association between educational attainment and willingness to adopt agrivoltaics**

| **Educational Level** | **Willing to Adopt n (%)** | **Not Willing to Adopt n (%)** | **Total n (%)** | **$\chi^2$** | **df** | **p-value** |
|---|---|---|---|---|---|---|
| Primary Education | 49 (76.6) | 15 (23.4) | 64 (100) | 18.64 | 6 | < 0.01 |
| Secondary Education | 73 (84.9) | 13 (15.1) | 86 (100) | | | |
| Tertiary Education | 170 (92.4) | 14 (7.6) | 184 (100) | | | |
| Vocational/Technical | 34 (81.0) | 8 (19.0) | 42 (100) | | | |
| **Total** | **326 (86.7)** | **50 (13.3)** | **376 (100)** | | | |

*Note: Chi-square test indicates a statistically significant association between educational attainment and willingness to adopt agrivoltaic technology (p < 0.01). Respondents with tertiary education demonstrated the highest willingness to adopt (92.4%), while those with primary education showed the lowest (76.6%).*

### 4.2.2 Association between farming experience and willingness to adopt agrivoltaics

The relationship between years of farming experience and willingness to adopt agrivoltaics was also examined using a chi-square test. A statistically significant association was found ($\chi^2 = 14.27$, df = 6, $p < 0.05$), as presented in Table 4.

**Table 4: Association between farming experience and willingness to adopt agrivoltaics**

| **Years of Farming Experience** | **Willing to Adopt n (%)** | **Not Willing to Adopt n (%)** | **Total n (%)** | **$\chi^2$** | **df** | **p-value** |
|---|---|---|---|---|---|---|
| ≤ 5 years | 104 (81.3) | 24 (18.7) | 128 (100) | 14.27 | 6 | < 0.05 |
| 6 – 10 years | 158 (91.3) | 15 (8.7) | 173 (100) | | | |
| 11 – 20 years | 55 (85.9) | 9 (14.1) | 64 (100) | | | |
| > 20 years | 8 (72.7) | 3 (27.3) | 11 (100) | | | |
| **Total** | **325 (86.7%)*** | **51 (13.3%)*** | **376 (100)** | | | |

**One respondent had missing data on willingness to adopt*

*Note: Chi-square test reveals a statistically significant association between farming experience and willingness to adopt (p < 0.05). Farmers with 6–10 years of experience showed the highest adoption willingness (91.3%), while those with over 20 years of experience exhibited the lowest (72.7%).*

### 4.2.3 Association between age category and awareness of agrivoltaics

The chi-square test examining the relationship between age and awareness of agrivoltaic technology revealed no statistically significant association ($\chi^2 = 5.82$, df = 8, $p > 0.05$), as shown in Table 5.

**Table 5: Association between age category and awareness of agrivoltaics**

| Age Category | Aware n (%) | Not Aware n (%) | Total n (%) | χ² | df | p-value |
|---|---|---|---|---|---|---|
| ≤ 25 years | 5 (22.7) | 17 (77.3) | 22 (100) | 5.82 | 8 | > 0.05 (NS) |
| 26 – 35 years | 8 (23.5) | 26 (76.5) | 34 (100) | | | |
| 36 – 45 years | 28 (21.2) | 104 (78.8) | 132 (100) | | | |
| 46 – 55 years | 29 (21.5) | 106 (78.5) | 135 (100) | | | |
| > 55 years | 9 (17.0) | 44 (83.0) | 53 (100) | | | |
| **Total** | **79 (21.0)** | **297 (79.0)** | **376 (100)** | | | |

*NS = Not Significant*

*Note: No statistically significant association was found between age category and awareness of agrivoltaic technology (p > 0.05). Awareness levels were uniformly low across all age groups, ranging from 17.0% to 23.5%.*

### 4.2.4 Association between occupation type and perceived importance of agrivoltaics

A chi-square test examining the relationship between occupation type and perceived importance of agrivoltaics revealed a statistically significant association ($\chi^2 = 16.91$, df = 6, $p < 0.01$), as presented in Table 6.

**Table 6: Association between occupation type and perceived importance of agrivoltaics for irrigation sustainability**

| Occupation Type | Very Important n (%) | Somewhat Important n (%) | Not Important n (%) | Total n (%) | χ² | df | p-value |
|---|---|---|---|---|---|---|---|
| Full-time Farmer | 122 (81.3) | 16 (10.7) | 12 (8.0) | 150 (100) | 16.91 | 6 | < 0.01 |
| Part-time Farmer | 145 (80.6) | 19 (10.5) | 16 (8.9) | 180 (100) | | | |
| Extension Officer | 26 (100) | 0 (0.0) | 0 (0.0) | 26 (100) | | | |
| Researcher | 20 (100) | 0 (0.0) | 0 (0.0) | 20 (100) | | | |
| **Total** | **313 (83.2)** | **35 (9.3)** | **28 (7.5)** | **376 (100)** | | | |

*Note: Chi-square test indicates a statistically significant association between occupation type and perceived importance of agrivoltaics (p < 0.01). Extension officers (100%) and researchers (100%) were more likely to perceive agrivoltaics as very important compared to full-time farmers (81.3%) and part-time farmers (80.6%).*

### 4.3 Correlation analysis of selected variables

To further explore relationships among key variables, Pearson's correlation analysis was conducted. The correlation matrix is presented in Table 7.

Table 7: Correlation matrix for selected variables

| Variable | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1. Years of farming experience | 1.00 | | | | |
| 2. Educational level (ordinal) | -0.08 | 1.00 | | | |
| 3. Age category | 0.62** | -0.12* | 1.00 | | |
| 4. Awareness of agrivoltaics (binary) | 0.04 | 0.16** | -0.03 | 1.00 | |
| 5. Willingness to adopt (binary) | 0.18** | 0.22** | -0.06 | 0.31** | 1.00 |

**Correlation is significant at the 0.05 level (2-tailed)*
***Correlation is significant at the 0.01 level (2-tailed)*
*N = 376 for all correlations; degrees of freedom = 374*
*Critical values: $r \geq 0.10 = p < 0.05$; $r \geq 0.13 = p < 0.01$*

The correlation analysis reveals several important relationships:

i. Farming experience and willingness to adopt ($r = 0.18$, $p < 0.01$): A weak but statistically significant positive correlation indicates that farmers with more experience tend to be slightly more willing to adopt agrivoltaics, though the relationship is modest.

ii. Educational level and willingness to adopt ($r = 0.22$, $p < 0.01$): A weak positive correlation confirms that higher educational attainment is associated with greater willingness to adopt, consistent with the chi-square findings.
iii. Awareness and willingness to adopt ($r = 0.31$, $p < 0.01$): A moderate positive correlation demonstrates that respondents who are aware of agrivoltaics are substantially more likely to express willingness to adopt it. This finding underscores the critical importance of awareness-building as a precursor to adoption.
iv. Age and farming experience ($r = 0.62$, $p < 0.01$): A strong positive correlation, as expected, confirms that older farmers generally have more years of farming experience.
v. Age and awareness ($r = -0.03$, $p > 0.05$): No significant correlation, reinforcing the chi-square finding that awareness is uniformly low across age groups.
vi. Educational level and awareness ($r = 0.16$, $p < 0.01$): A weak but significant positive correlation suggests that respondents with higher education are somewhat more likely to be aware of agrivoltaics, though the relationship is modest.

### 4.4 Logistic regression analysis of factors influencing willingness to adopt agrivoltaics

To identify the independent predictors of willingness to adopt agrivoltaics while controlling for potential confounding variables, binary logistic regression analysis was performed. Willingness to adopt (willing vs. not willing) was entered as the dependent variable, with educational level, farming experience (continuous), awareness, and occupation type as independent variables. The results are presented in Table 8.

**Table 8: Logistic regression analysis of factors influencing willingness to adopt agrivoltaics**

| **Variable** | **B** | **S.E.** | **Wald** | **df** | **p-value** | **Odds Ratio (Exp B)** | **95% C.I. for Odds Ratio** | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Lower | Upper |
| Educational Level (ref: Primary) | | | **12.45** | **3** | **< 0.01** | | | |
| Secondary Education | 0.58 | 0.31 | 3.52 | 1 | 0.06 | 1.79 | 0.97 | 3.28 |
| Tertiary Education | 1.24 | 0.38 | 10.68 | 1 | < 0.01 | 3.46 | 1.65 | 7.25 |
| Vocational/Technical | 0.31 | 0.42 | 0.55 | 1 | 0.46 | 1.36 | 0.60 | 3.09 |
| Farming Experience (years) | 0.06 | 0.02 | 6.54 | 1 | < 0.05 | 1.06 | 1.01 | 1.11 |
| Awareness of Agrivoltaics (ref: Not Aware) | | | | | | | | |
| Aware | 1.42 | 0.45 | 9.96 | 1 | < 0.01 | 4.14 | 1.71 | 9.99 |
| Occupation Type (ref: Full-time Farmer) | | | **5.21** | **3** | **0.16** | | | |
| Part-time Farmer | -0.09 | 0.28 | 0.10 | 1 | 0.75 | 0.91 | 0.53 | 1.58 |
| Extension Officer | 1.21 | 0.78 | 2.41 | 1 | 0.12 | 3.35 | 0.73 | 15.45 |
| Researcher | 0.98 | 0.82 | 1.43 | 1 | 0.23 | 2.66 | 0.54 | 13.22 |
| Constant | 0.42 | 0.45 | 0.87 | 1 | 0.35 | 1.52 | | |

*Note: Logistic regression analysis confirms that tertiary education (OR = 3.46, $p < 0.01$), farming experience (OR = 1.06, $p < 0.05$), and awareness of agrivoltaics (OR = 4.14, $p < 0.01$) are significant positive predictors of willingness to adopt agrivoltaic systems. The model correctly classified 87.2% of cases (Nagelkerke $R^2 = 0.24$).*

The logistic regression analysis provides the most rigorous assessment of factors associated with adoption willingness:

i. **Awareness of agrivoltaics (OR = 4.14, $p < 0.01$):** Respondents who were aware of the technology had over four times higher odds of being willing to adopt compared to those who were unaware. This finding dramatically underscores the importance of awareness-building as a prerequisite for adoption and suggests that information dissemination could yield substantial returns in terms of adoption readiness.
ii. **Tertiary education (OR = 3.46, $p < 0.01$):** Respondents with tertiary education had nearly 3.5 times higher odds of being willing to adopt compared to those with only primary education. This strong effect, independent of other factors, highlights education as a key determinant of innovation acceptance.
iii. **Farming experience (OR = 1.06, $p < 0.05$):** Each additional year of farming experience was associated with a 6% increase in the odds of being willing to adopt. While this effect is modest, it suggests that accumulated farming experience contributes to openness to new technologies, possibly through greater recognition of production challenges and the value of potential solutions.

iv. **Occupation type** did not emerge as a significant predictor in the multivariate model, suggesting that the apparent differences observed in the chi-square analysis (Table 6) may be explained by other factors such as education and awareness levels.

### 4.5 **Summary of inferential findings**

A concise summary of the hypotheses tested and the corresponding outcomes is presented in Table 9.

**Table 9: Summary of inferential findings**

| **Variables Tested** | **Test Used** | **Test Value** | **df** | **p-value** | **Outcome** |
|---|---|---|---|---|---|
| Education × Willingness | Chi-square | 18.64 | 6 | < 0.01 | Significant |
| Experience × Willingness | Chi-square | 14.27 | 6 | < 0.05 | Significant |
| Age × Awareness | Chi-square | 5.82 | 8 | > 0.05 | Not Significant |
| Occupation × Perceived Importance | Chi-square | 16.91 | 6 | < 0.01 | Significant |
| Experience × Willingness | Pearson's r | 0.18 | 374 | < 0.01 | Significant (weak) |
| Education → Willingness | Logistic Regression | Wald = 10.68 | 1 | < 0.01 | Significant (OR = 3.46) |
| Awareness → Willingness | Logistic Regression | Wald = 9.96 | 1 | < 0.01 | Significant (OR = 4.14) |
| Experience → Willingness | Logistic Regression | Wald = 6.54 | 1 | < 0.05 | Significant (OR = 1.06) |

### 4.6 **Discussion**

The predominance of rain-fed agriculture in Aguata Agricultural Zone reflects broader structural challenges confronting Nigerian smallholder farming systems, where irrigation development remains insufficient despite recognized productivity gains (Olayide *et al.*, 2016; Udo, 2020). Critically, farmers' reports of high diesel costs and unreliable grid electricity highlight the water-energy nexus at farm level – an interdependence often overlooked in agricultural planning. Agrivoltaic systems address this precisely by embedding energy generation within agricultural land use, potentially breaking fossil-fuel dependency that limits dry-season cultivation (Falchetta *et al.*, 2023; Khatri *et al.*, 2022). The findings thus position agrivoltaics not merely as an irrigation technology but as a systemic intervention addressing interconnected resource constraints within the water-energy-food nexus framework.

A striking finding is the juxtaposition of extremely low prior awareness (79%) with remarkably high expressed willingness to adopt (86.7%) once the concept was explained. This awareness-adoption gap commands significant implications for dissemination strategies. The uniform awareness deficit across demographic groups ($\chi^2 = 5.82$, $p > 0.05$) suggests systemic information failure rather than concentration in particular farmer categories, aligning with national assessments indicating agrivoltaic development in Nigeria remains nascent with few pilot initiatives (Babarinde, 2024; IISD, 2023). The moderate positive correlation between awareness and willingness ($r = 0.31$, $p < 0.01$), together with logistic regression showing aware respondents had over four times higher adoption odds ($OR = 4.14$, $p < 0.01$), underscores a critical policy lever: awareness-building is not merely precursor to adoption but potentially its most powerful driver, suggesting investments in demonstration projects and extension messaging could yield substantial returns in adoption readiness (Ominikari *et al.*, 2017; Tesfaye and Gutema, 2022).

Socio-demographic determinants of adoption readiness offer insights for targeting interventions. Tertiary education strongly predicted willingness ($OR = 3.46$, $p < 0.01$), consistent with innovation diffusion theory positing that education enhances capacity to process information and evaluate new technologies, suggesting early promotion might strategically engage educated farmers as first adopters and peer educators. The relationship between farming experience and adoption was nuanced: highest willingness among farmers with 6–10 years' experience (91.3%) reflects optimal combination of practical knowledge and continued openness ($\chi^2 = 14.27$, $p < 0.05$), while lower willingness among >20-year farmers (72.7%) hints at attachment to established practices (Tesfaye and Gutema, 2022). This suggests extension approaches require the adaptation of experiential learning for experienced farmers and structured training for newer entrants. That occupation type influenced perceived importance ($\chi^2 = 16.91$, $p < 0.01$) but not adoption willingness in multivariate analysis suggests technical personnel appreciate the technology's value, but farmers' adoption decisions are shaped by practical considerations; education, experience, and awareness, rather than occupational identity per se.

The barriers identified; installation costs (65%), technical knowledge gaps (60%), land concerns (30%), maintenance requirements (20.8%), align closely with those documented in other developing-country contexts where agrivoltaics remains in early diffusion stages (Rahman *et al.*, 2023; Anyene *et al.*, 2025). However, these perceived barriers should be interpreted as expressions of institutional gaps rather than fixed obstacles. Cost concerns reflect capital-intensive infrastructure requiring solar panels, mounting structures, pumping equipment, and storage (Trommsdorff *et al.*, 2022), pointing to innovative financing mechanisms; subsidies, cooperative models, pay-as-you-go arrangements, that transform upfront costs into manageable streams. Technical knowledge gaps highlight inadequacy of existing extension systems in preparing farmers for integrated energy-agriculture technologies requiring understanding of solar energy, irrigation engineering, and crop management under modified microclimates (Kim & Kim, 2023). This requires targeted training for both farmers and extension personnel, who demonstrated near-universal recognition of agrivoltaic importance (100%), indicating receptiveness to capacity building. Land concerns, while reported by fewer respondents, touch on fundamental institutional arrangements where tenure insecurity and competing pressures create hesitation, though this may reflect limited understanding of dual-use configurations allowing continued cropping beneath or between panels (Trommsdorff *et al.*, 2022).

The high proportion (84%) considering agrivoltaics important for irrigation sustainability, despite limited prior awareness, suggests the technology's value proposition resonates once articulated. Farmers' associations with reliable pumping, reduced diesel dependence, and improved water availability reflect accurate intuitions about potential benefits. Some also anticipated microclimatic benefits; reduced evapotranspiration and crop heat stress, corresponding with documented effects showing partial shading lowers soil and air temperatures, reducing crop water stress particularly for heat-sensitive crops (Barron-Gafford *et al.*, 2019; Pandey *et al.*, 2025; Semeraro *et al.*, 2024). This alignment between farmer perceptions and scientific evidence suggests smallholder farmers, when presented with clear information, can accurately assess technologies addressing experienced constraints. Overall, findings suggest agrivoltaic adoption is constrained primarily by socio-economic and institutional factors rather than technical feasibility or farmer resistance. The region possesses favourable solar resources; average irradiance 4.0–6.5 kWh/m²/day (NiMet, 2026), and commonly cultivated crops like maize and vegetables have demonstrated compatibility in similar tropical environments, with studies reporting maintained or increased yields using up to 20% less irrigation water (Elamri *et al.*, 2018; Witwit *et al.*, 2025). Technical pieces for successful deployment are therefore in place. Unlike technologies facing cultural resistance, agrivoltaics encounters primarily structural barriers amenable to policy intervention; information dissemination, innovative financing, technical support, regulatory clarity, providing an encouraging foundation for future development in Nigerian smallholder agriculture (Anyene *et al.*, 2025; Walston *et al.*, 2022).

## 5.0 Conclusion

This study demonstrates that agrivoltaic systems present a promising pathway for strengthening irrigation sustainability within the Aguata Agricultural Zone of Anambra State, particularly in the context of persistent energy limitations and climate-related variability affecting smallholder agriculture. Although the technology remains largely unfamiliar among local agricultural stakeholders, the strong interest expressed after its introduction suggests that agrivoltaics could gain acceptance if supported by appropriate institutional, technical, and financial mechanisms. The findings indicate that the main constraints to adoption are not related to technical feasibility but rather to limited awareness, inadequate capacity for system implementation and management, and restricted access to investment resources required for initial deployment. Addressing these barriers through targeted awareness programmes, farmer training, demonstration projects, and supportive policy frameworks could facilitate gradual integration of agrivoltaic systems into existing farming practices. If effectively implemented, such integrated energy–agriculture solutions have the potential to improve irrigation reliability, reduce dependence on fossil fuels for water pumping, and contribute to more resilient and sustainable agricultural production systems within the region.

## 5.1 Recommendations

To harness the potential of agrivoltaics for irrigation sustainability in Aguata and similar zones, the following actions are recommended:

i. **Implement targeted awareness and demonstration programs**: There is a dire need to establish agrivoltaic pilot farms in Aguata to showcase irrigation and energy benefits. These sites will serve as learning hubs for farmers and extension agents.
ii. **Tailor interventions to different farmer groups**: Farmers with tertiary education and moderate experience should be engaged as early adopters and peer educators. Those with lower education or extensive experience require simpler information materials and cooperative-based engagement.
iii. **Institutionalize dedicated agrivoltaic financing mechanisms**: The Central Bank should mandate low-interest green loans for agrivoltaics, while state governments provide 30% capital subsidies. Cooperative-based financing through programs like the Anchor Borrowers' Programme should complement these efforts.

iv. **Strengthen the regulatory and land-use framework**: The Land Use Act should be amended to formally recognize agrivoltaics as a dual-use agricultural activity. This will reduce legal uncertainty and encourage private sector investment.

v. **Develop national technical and performance standards**: SON and NASENI should publish national agrivoltaic design and safety standards by 2026. These standards must address configurations suitable for smallholder farming systems.

vi. **Promote coordinated research and public–private partnerships**: TETFund should prioritize research on staple crops like cassava and maize under agrivoltaic conditions. A public-private platform should link solar firms, irrigation suppliers, and farmer associations to support scalable business models.

vii. **Address knowledge gaps among extension personnel**: Targeted training programs should be developed to build extension officers' technical understanding of agrivoltaics. This will enable them to effectively advise farmers on system design, operation, and maintenance.

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## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) did not utilize any generative AI or automated writing tools. This manuscript is entirely the product of the authors' own intellectual effort and is based exclusively on original field survey research, data collection, and analysis. The authors take full responsibility for the content, findings, and conclusions presented in this publication.

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