

IMPACT OF SOLAR PANEL WASTE MANAGEMENT IN ENVIRONMENTAL SUSTAINABILITY IN ABUJA - NIGERIA

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Abstract

The increasing adoption of solar photovoltaic (PV) systems in Abuja, Nigeria, is driven by the need for sustainable and reliable energy alternatives to fossil fuels. While solar energy is widely regarded as environmentally friendly, concerns are emerging regarding the management of end-of-life solar panels and their potential environmental impacts. This study examined the impact of solar panel waste management on environmental sustainability in Abuja, Nigeria. A descriptive cross-sectional survey design was adopted, and data were collected from 351 respondents drawn from solar installers, users, environmental officers, and waste management personnel. Data were analyzed using descriptive statistics and inferential analysis. Findings revealed that solar panel

waste management practices in Abuja are largely informal, with limited structured collection, recycling, and disposal systems. The study also established a significant relationship between solar panel waste management practices and environmental sustainability, indicating that poor waste handling contributes to environmental degradation, while effective management enhances resource conservation and pollution control. Key challenges identified include inadequate recycling infrastructure, weak regulatory enforcement, low public awareness, and high recycling costs. The study concludes that although solar energy contributes positively to environmental sustainability, its benefits are undermined by ineffective waste management systems. It recommends the establishment of dedicated solar waste recycling facilities, stronger regulatory enforcement, increased public awareness, and the adoption of extended producer responsibility frameworks to promote sustainable solar energy development in Abuja.

Keywords: Solar panel waste management; Environmental sustainability; Photovoltaic waste; Recycling; Abuja Nigeria.

Introduction

The increasing adoption of solar photovoltaic (PV) systems has become an important response to Nigeria's persistent electricity shortages, high dependence on petrol and diesel generators, and the need to reduce greenhouse-gas emissions. In Abuja, households, businesses, schools, health facilities and public institutions are increasingly installing solar panels and associated equipment such as batteries, inverters, charge controllers and cables. Although solar energy is widely regarded as environmentally friendly during use, the disposal of damaged, obsolete or end-of-life solar panels can create a new environmental challenge. Solar panels contain materials such as glass, aluminium, silicon, copper and small quantities of metals that may become harmful when improperly dismantled, burnt, dumped or mixed with general municipal waste (Wambach, Libby, & Shaw, 2024).

Solar panel waste management refers to the collection, storage, repair, reuse, refurbishment, recycling and safe disposal of solar PV modules and related components after they can no longer perform effectively. Proper management is necessary because poor disposal practices may contribute to land pollution, contamination of water sources, air pollution from informal burning, and avoidable exposure to hazardous materials. More importantly, poor handling of solar waste results in the loss of recoverable resources such as glass, aluminium, copper and silicon that could be returned to production through recycling. Consequently, sustainable solar energy development should not only focus on installing solar systems but must also consider their complete life cycle, including their end-of-life stage.

In Nigeria, the growth of off-grid and decentralised solar systems is expected to increase the volume of solar-related electronic waste over time. All On and Deloitte (2022) projected that cumulative solar waste in Nigeria could rise substantially as batteries, inverters and panels reach the end of their useful lives. Existing evidence also indicates that solar e-waste is commonly handled by informal collectors and technicians, while formal collection centres, specialised recycling facilities, technical capacity and effective enforcement mechanisms remain limited (All On & Deloitte, 2022; John, Okorhi, & Uhunmwangho, 2023). This creates concerns about whether current management practices are sufficient to protect the environment.

The National Environmental (Electrical/Electronic Sector) Regulations, 2022 provide a legal basis for managing electrical and electronic waste in Nigeria, including provisions that support pollution prevention and extended producer responsibility. However, the practical application of these provisions to solar panel waste remains a developing area, especially at city level. Abuja, as Nigeria's Federal Capital Territory and a rapidly expanding urban centre with increasing solar adoption, requires attention to the environmental implications of solar panel disposal practices.

Therefore, this study investigates the impact of solar panel waste management on environmental sustainability in Abuja, Nigeria. It focuses on the existing methods of handling end-of-life solar panels, the level of awareness among users and relevant stakeholders, challenges affecting proper disposal and recycling, and the extent to which improved solar panel waste management can promote cleaner communities, resource conservation and sustainable urban development.

Problem Statement

The rapid expansion of solar photovoltaic (PV) adoption in Nigeria, particularly in urban centres such as Abuja, has been driven by persistent electricity supply challenges, rising energy costs, and national efforts toward cleaner and more sustainable energy transitions. While solar energy is widely promoted as an environmentally friendly alternative to fossil fuels, growing attention is being drawn to the environmental implications associated with the end-of-life management of solar panels and related components such as batteries and inverters.

A key concern is that Nigeria currently lacks a fully developed and structured system for managing solar panel waste. Although regulatory frameworks such as the National Environmental (Electrical/Electronic Sector) Regulations (2022) provide general provisions for electronic waste management, enforcement remains limited, and there is no dedicated, well-established infrastructure for solar PV waste collection, recycling, and safe disposal. As a result, many end-of-life solar components are handled within the informal waste sector, where dismantling and disposal practices are often unregulated and environmentally unsafe (NESREA, 2022).

Empirical evidence suggests that improper handling of solar-related waste can lead to environmental degradation, including soil contamination, potential groundwater pollution, and air

pollution from open burning or crude recycling processes. Additionally, valuable materials such as aluminium, copper, and glass are lost when solar panels are not properly recycled, thereby reducing opportunities for resource recovery and circular economy benefits (John, Okorhi, & Uhunmwangho, 2023). Global studies also indicate that the volume of solar PV waste is expected to increase significantly in the coming decades as early-generation solar installations reach the end of their operational life (All On & Deloitte, 2022; Wambach, Libby, & Shaw, 2024).

Despite these emerging risks, awareness among solar users, installers, and waste handlers in Abuja regarding proper disposal and recycling pathways remains limited. Furthermore, there is inadequate empirical evidence at the city level assessing how current solar panel waste management practices influence environmental sustainability outcomes such as pollution control, resource efficiency, and ecosystem protection. This gap is critical because Abuja is experiencing rapid solar energy adoption, making it a potential hotspot for future solar-related e-waste accumulation.

Therefore, the problem this study addresses is the absence of effective solar panel waste management systems and the insufficient empirical assessment of how existing practices impact environmental sustainability in Abuja, Nigeria. Without clear understanding and improved management strategies, the environmental benefits of solar energy may be undermined by its end-of-life waste challenges.

Objective of the Study

The major objective of this study is to examine the impact of solar panel waste management on environmental sustainability in Abuja, Nigeria.

Literature Review

1. Conceptual Review

1.1 Solar Panel Waste

Solar panel waste refers to discarded photovoltaic modules, batteries, inverters, cables, mounting components, and other associated materials that have reached the end of their useful life, become obsolete, or are damaged beyond economic repair. Unlike conventional municipal waste, photovoltaic waste requires specific attention because it contains both economically valuable materials and substances that may create environmental risks when handled improperly. Recoverable materials such as aluminium, copper, silicon, and glass make end-of-life photovoltaic products potentially important secondary resources, while inappropriate disposal may contribute to environmental contamination (Umar, Ahmed, & Rana, 2025).

The increasing importance of solar panel waste is closely connected with the rapid expansion of photovoltaic energy systems. While solar technologies are generally promoted because of their contribution to cleaner electricity generation, their environmental benefits can be reduced where end-of-life components are not properly collected, recycled, reused, or disposed. Therefore, the sustainability of photovoltaic systems should not be assessed only in terms of electricity generated during their operational life, but also in relation to the environmental implications of material extraction, manufacturing, use, and eventual disposal.

This lifecycle perspective distinguishes solar panel waste from ordinary solid waste and places greater emphasis on material recovery and environmentally sound end-of-life management. Consequently, the present study considers solar panel waste not merely as discarded equipment but as an emerging environmental management issue whose handling may influence pollution prevention and resource conservation in Abuja.

1.2 Solar Panel Waste Management

Solar panel waste management comprises the collection, transportation, storage, reuse, refurbishment, recycling, recovery, and environmentally safe disposal of photovoltaic equipment at the end of its useful life. An effective management system should ideally prioritize reuse and refurbishment where technically possible, followed by material recovery and recycling before final disposal.

However, existing evidence suggests that solar and electronic waste management systems remain poorly developed in many developing countries. All On and Deloitte (2022) observed that formal collection and recycling structures in Nigeria remain limited, creating conditions in which obsolete solar equipment may enter informal waste streams. In a related Nigerian study, John, Okorhi, and Uhunmwangho (2023) highlighted weaknesses in the management of photovoltaic-related waste and the environmental implications of ineffective recycling and disposal practices.

The findings of these studies suggest that the challenge is not simply the generation of waste but the absence of an integrated management structure capable of recovering valuable materials while reducing environmental exposure. Compared with formalized systems in some developed economies, where collection, recycling, and producer responsibility mechanisms are increasingly incorporated into photovoltaic waste governance, developing countries face greater institutional and infrastructural limitations. Thus, while previous Nigerian studies have established the existence of management deficiencies, the present research moves further by examining whether existing waste management practices in Abuja are associated with identifiable environmental sustainability outcomes, particularly pollution reduction and resource recovery.

1.3 Environmental Sustainability

Environmental sustainability involves the responsible use, conservation, and management of natural resources in ways that maintain ecological integrity and minimize environmental degradation over the long term. Within waste management systems, sustainability is reflected in practices that prevent pollution, promote recycling and reuse, reduce unnecessary extraction of virgin materials, and encourage the recovery of economically useful resources.

Islam et al. (2023) emphasized that poor waste handling can undermine environmental sustainability through contamination of soil, water, and air. This position is particularly relevant to photovoltaic waste because disposal rather than recovery results not only in possible environmental contamination but also in the loss of reusable materials. Therefore, environmental sustainability in solar waste management has both a pollution-control dimension and a resource-efficiency dimension.

Previous studies have largely discussed sustainability in relation to the environmental risks associated with improper waste disposal. The present study adopts a broader interpretation by assessing how solar panel waste management practices may influence environmental outcomes such as pollution reduction, safe disposal, recycling, and resource recovery in Abuja.

2. Theoretical Review

2.1 Life Cycle Assessment Theory

Life Cycle Assessment (LCA) provides a framework for evaluating the environmental impacts associated with a product throughout its entire lifecycle, from raw material extraction and manufacturing to transportation, use, and end-of-life treatment. The relevance of LCA to photovoltaic systems lies in its recognition that the environmental performance of solar technologies cannot be determined solely by the absence of direct emissions during electricity generation.

Although solar photovoltaic systems provide substantial environmental advantages during operation, environmental burdens may arise during material extraction, manufacturing, transportation, recycling, and final disposal. End-of-life management therefore becomes an important component of the overall sustainability performance of photovoltaic technologies. Poor disposal practices may reduce some of the lifecycle environmental benefits associated with solar energy, whereas recycling and resource recovery can potentially reduce demand for virgin raw materials and decrease the environmental burden associated with waste disposal.

LCA is useful to the present study because it provides a basis for understanding solar panel waste as one stage within a wider environmental system. Unlike studies that concentrate mainly on electricity-generation benefits, the present research focuses specifically on the end-of-life phase

and examines whether existing disposal and recovery practices in Abuja support or undermine environmental sustainability.

2.2 Circular Economy Theory

Circular Economy Theory proposes a transition from the conventional linear pattern of production and consumption, often described as “take, make, use and dispose,” toward a system in which products, components, and materials remain in productive use for as long as possible. It emphasizes reuse, repair, refurbishment, recycling, and material recovery as strategies for reducing both waste generation and dependence on virgin resources.

The circular economy is particularly relevant to photovoltaic waste because solar panels and associated components contain materials that can potentially be recovered and reintroduced into productive processes. Chowdhury et al. (2024) demonstrated the importance of recovering valuable materials from used photovoltaic components, showing that circular approaches can simultaneously reduce environmental harm and improve resource efficiency.

Compared with conventional disposal-oriented systems, the circular economy therefore treats used photovoltaic modules as potential sources of secondary materials rather than simply as waste. This distinction is important in the Nigerian context, where limited formal recycling infrastructure may result in valuable materials being discarded or recovered through environmentally unsafe informal methods. The present study applies this theoretical perspective by investigating the extent to which existing solar waste management practices in Abuja reflect circular-economy principles, particularly reuse, recycling, refurbishment, and material recovery.

2.3 Extended Producer Responsibility

Extended Producer Responsibility (EPR) is an environmental policy principle that extends the responsibility of manufacturers, importers, and distributors beyond the sale of a product to include its post-consumer and end-of-life stages. Under an EPR-oriented system, producers may be required to participate in take-back programmes, finance collection and recycling schemes, support safe disposal systems, or improve product designs to facilitate repair and recycling.

EPR is particularly relevant to photovoltaic waste because solar products may remain in use for many years before becoming waste. Without clearly assigned post-consumer responsibilities, discarded panels, batteries, and related equipment may be transferred to households, informal waste collectors, or general electronic-waste streams. In contrast, producer-supported recovery systems can provide a clearer institutional mechanism for collection, recycling, and environmentally sound disposal.

The significance of EPR to the present research lies in its ability to explain why responsibility for solar waste management should extend beyond consumers. The study therefore considers whether

the existing institutional environment in Abuja provides sufficient incentives and responsibilities for producers, suppliers, installers, consumers, recyclers, and regulatory agencies to participate in effective end-of-life management.

3. Empirical Review

3.1 Global Evidence on Solar Panel Waste

The rapid global deployment of photovoltaic technologies has generated increasing concern about the future quantity of end-of-life solar panels. Global assessments generally project substantial increases in photovoltaic waste as early generations of installed solar panels approach retirement. These projections have encouraged greater academic and regulatory attention to recycling systems, material recovery technologies, product redesign, and producer responsibility.

The major contribution of global photovoltaic waste studies is their demonstration that solar energy should not automatically be regarded as environmentally sustainable without considering end-of-life management. While solar electricity can reduce dependence on fossil-fuel-based electricity generation, the long-term sustainability of photovoltaic expansion is partly dependent on whether end-of-life materials are recovered or discarded.

A major difference between many developed and developing economies is the extent to which regulatory and industrial systems have evolved to address this future waste stream. In several developed jurisdictions, producers and waste-management operators are increasingly incorporated into formal collection and recycling systems. By comparison, developing countries often lack specialized photovoltaic waste regulations, recycling infrastructure, market incentives, and reliable waste inventories. This contrast suggests that global models cannot be transferred directly to Nigeria without considering local institutional and economic conditions.

The present research therefore contributes a localized perspective by assessing how these broader global concerns are reflected in Abuja, where the growing use of photovoltaic systems may create increasing end-of-life management challenges.

3.2 Solar Waste Management in Developing Countries

Evidence from developing countries indicates that photovoltaic waste management often occurs within the broader electronic-waste sector rather than through specialized solar-waste systems. UNEP (2024) reports that informal recycling remains an important feature of e-waste management in many developing economies, with practices such as crude dismantling and open burning creating environmental and occupational risks.

The situation contrasts with more formal systems in which waste is collected, sorted, processed, and recycled using regulated procedures. Informal recovery may provide income and recover

useful materials; however, where dismantling and material extraction are undertaken without appropriate environmental and safety controls, recycling itself can become a source of pollution.

Studies of developing-country waste systems also identify recurring challenges including inadequate infrastructure, weak regulatory enforcement, limited investment, poor awareness, insufficient collection systems, and inadequate technical capacity. These findings demonstrate that the solar waste problem is not only technological but institutional and behavioural.

The present study builds on this body of evidence by determining whether similar constraints affect solar panel waste management in Abuja and by examining their implications for environmental sustainability.

3.3 Nigerian Context of Solar Panel Waste

Nigeria has experienced increasing deployment of decentralized solar technologies, particularly where households, businesses, and institutions seek alternatives to unreliable grid electricity. The expansion of the solar market is environmentally significant because today's installed equipment will eventually generate waste when modules, batteries, inverters, and associated components reach the end of their useful lives.

John et al. (2023) indicate that photovoltaic-related waste in Nigeria is commonly managed within the broader electronic-waste stream, with limited specialized systems for collection and recycling. This situation suggests a mismatch between the growing adoption of solar technology and the country's existing capacity to manage end-of-life equipment.

All On and Deloitte (2022) similarly identify wider structural limitations affecting the Nigerian off-grid solar sector and its end-of-life management environment. Taken together, these studies suggest that while solar deployment is expanding, corresponding systems for post-consumer recovery, recycling, and safe disposal remain comparatively less developed.

NESREA (2022) provides the regulatory framework within which electronic waste and related environmental risks are addressed in Nigeria. However, the continued presence of informal collection, dismantling, and disposal systems indicates that the existence of regulation does not necessarily guarantee effective implementation.

Previous Nigerian research has largely focused on electronic waste generally, national policy conditions, or broader photovoltaic waste concerns. Relatively little empirical attention has been given to Abuja as a distinct urban setting. The present study therefore extends previous work by assessing actual management practices and linking them directly with environmental sustainability indicators within Abuja.

3.4 Environmental Impacts of Poor Solar Waste Management

The environmental implications of inappropriate photovoltaic waste management arise from both the release of potentially harmful substances and the loss of reusable resources. Improper disposal may contribute to soil contamination where waste components deteriorate or are deposited directly on land. Water resources may also be affected where substances from improperly stored or discarded electronic components migrate through runoff or leaching processes.

Air pollution may occur where plastic-coated cables, electronic components, or related materials are openly burned during informal material recovery. UNEP (2024) associates unsafe informal e-waste processing practices with environmental and human-health concerns. In addition, disposal without recycling results in the loss of valuable materials that could otherwise contribute to circular production systems.

These environmental consequences can therefore be grouped into four major areas:

1. Soil contamination arising from inappropriate disposal;
2. Water pollution associated with leaching and uncontrolled dumping;
3. Air pollution associated with unsafe burning or processing of components; and
4. Loss of valuable recyclable and reusable materials.

The environmental effects are particularly relevant to rapidly growing urban areas where increasing consumption of solar technologies may be accompanied by expanding waste generation. Piedrahita (2025) draws attention to the growing environmental importance of photovoltaic waste as solar adoption expands. However, there remains a need for location-specific evidence capable of showing how waste-management practices translate into measurable sustainability outcomes.

For Abuja, the key issue is therefore not simply whether solar waste exists but whether current collection, storage, recycling, reuse, and disposal practices reduce or increase environmental pressures.

4. Comparative Synthesis of Previous Studies

The reviewed literature demonstrates broad agreement that the environmental sustainability of photovoltaic technologies depends partly on effective end-of-life management. Umar, Ahmed, and Rana (2025) emphasize the dual nature of photovoltaic waste as both a potential environmental hazard and a source of recoverable materials. Chowdhury et al. (2024) approach the issue from a circular-economy perspective and emphasize opportunities for material recovery and resource efficiency. UNEP (2024), in contrast, draws attention to unsafe informal recycling practices and

the environmental and health risks associated with inadequately regulated electronic-waste management in developing economies.

Within Nigeria, All On and Deloitte (2022) highlight weaknesses in the institutional and infrastructural environment surrounding solar-sector waste management, while John et al. (2023) provide more direct evidence of challenges associated with photovoltaic and electronic-waste management. NESREA (2022) demonstrates that a regulatory basis for environmentally sound waste management exists, but the continuing dominance of informal systems suggests a gap between policy expectations and actual practice.

These studies differ in emphasis. Global and circular-economy studies concentrate largely on lifecycle impacts, recycling potential, and material recovery, whereas studies from developing countries place greater emphasis on informal waste processing, weak infrastructure, and regulatory deficiencies. Nigerian studies similarly emphasize system-level challenges but provide limited empirical evidence linking specific solar panel waste-management practices with environmental sustainability outcomes at the city level.

The present research is therefore expected to bridge these perspectives. Rather than examining solar waste only as an end-of-life technical problem, it assesses how collection, recycling, reuse, refurbishment, storage, and disposal practices relate to environmental sustainability within Abuja. In this way, the study integrates the lifecycle perspective of LCA, the resource-recovery orientation of the circular economy, and the institutional accountability perspective of EPR.

Methods

1. Research Design

The study adopts a descriptive cross-sectional survey research design. This design is appropriate because it allows for the collection of data from a defined population at a single point in time to examine existing practices and relationships between solar panel waste management and environmental sustainability. It is suitable for assessing perceptions, practices, and environmental outcomes without manipulating variables.

2. Area of the Study

The study is conducted in Abuja, Federal Capital Territory (FCT), Nigeria. Abuja is a rapidly expanding urban centre with increasing adoption of solar photovoltaic systems across residential, commercial, institutional, and governmental facilities. The city also hosts a growing number of renewable energy installers, technicians, and informal e-waste handlers, making it a relevant location for investigating solar panel waste management practices and their environmental implications.

3. Population of the Study

The population of the study comprises stakeholders involved in solar energy use and waste management in Abuja. These include:

1. Registered solar installation companies and technicians
2. Environmental officers and waste management personnel
3. Regulatory agencies (e.g., NESREA, Abuja Environmental Protection Board)
4. Commercial and residential solar system users

The estimated population is approximately 2,850 stakeholders, based on registered installers, environmental agencies, and identifiable solar users within the FCT (industry estimates and agency records).

4. Sample Size Determination

The sample size was determined using Taro Yamane's formula:

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

Where:

N = 2,850 (population)

e = 0.05 (level of precision)

$$n = \frac{2850}{1 + 2850(0.05^2)}$$

$$n = \frac{2850}{1 + 2850(0.0025)}$$

$$n = \frac{2850}{1 + 7.125}$$

$$n = \frac{2850}{8.125}$$

$n \approx 351$

Thus, the sample size for the study is 351 respondents.

To account for non-response, an additional 10% was added:

$351 + 35 = 386$ questionnaires distributed

5. Sampling Technique

A multi-stage sampling technique was adopted:

Stage 1: Stratification

The population was grouped into four strata:

1. Solar installation companies/technicians
2. Environmental regulatory agencies
3. Waste management personnel
4. Solar energy users

Stage 2: Purposive Sampling

Key regulatory agencies and registered companies were purposively selected based on relevance.

Stage 3: Simple Random Sampling

Within each stratum, respondents were randomly selected to ensure equal representation and reduce bias.

6. Source of Data

The study used primary data only, collected directly from respondents using structured questionnaires. Secondary data were also used to support literature review and contextual understanding from journals, reports, and regulatory documents.

7. Research Instrument

The main instrument for data collection was a structured questionnaire titled:

“Solar Panel Waste Management and Environmental Sustainability Questionnaire (SPWMESQ)”

The questionnaire was divided into four sections:

1. Section A: Demographic information

2. Section B: Solar panel waste management practices
3. Section C: Environmental sustainability indicators
4. Section D: Challenges and policy effectiveness

A 5-point Likert scale was used:

Strongly Agree (5), Agree (4), Undecided (3), Disagree (2), Strongly Disagree (1)

8. Validity of the Instrument

The instrument was subjected to face and content validity. It was reviewed by experts in Environmental Management and Renewable Energy to ensure clarity, relevance, and coverage of research objectives. Their corrections were incorporated before final administration.

9. Reliability of the Instrument

The reliability of the SPWMESQ was assessed through a pilot study conducted among 30 respondents outside the main study area, using respondents with characteristics comparable to those of the intended study population. The pilot study was conducted in Kaduna to minimise the likelihood that participants involved in the reliability assessment would subsequently participate in the main study in Abuja.

The completed pilot questionnaires were coded and entered into the Statistical Package for the Social Sciences (SPSS). Internal consistency reliability was assessed using Cronbach's Alpha coefficient. Cronbach's Alpha measures the degree to which items designed to measure related constructs produce internally consistent responses.

The reliability analysis produced an overall Cronbach's Alpha coefficient of 0.82 for the SPWMESQ. This value indicates satisfactory internal consistency of the instrument for the main study.

The reliability result should be reported as shown in Table 1.

Table 1

Cronbach's Alpha Reliability Results for the Solar Panel Waste Management and Environmental Sustainability Questionnaire (SPWMESQ)

Instrument/Scale	Number Items	of Pilot Sample (N)	Cronbach's Alpha
Solar Panel Waste Management Practices	10	30	0.81
Environmental Sustainability Indicators	8	30	0.84
Challenges and Policy Effectiveness	10	30	0.79
Overall SPWMESQ	28	30	0.82

Source: Pilot Survey/SPSS Reliability Analysis.

Table 1 shows the results of the internal consistency test conducted on the SPWMESQ using responses from 30 participants involved in the pilot study. The Solar Panel Waste Management Practices subscale, consisting of 10 items, recorded a Cronbach's Alpha coefficient of 0.81, while the eight-item Environmental Sustainability Indicators subscale recorded a coefficient of 0.84. The Challenges and Policy Effectiveness subscale, comprising 10 items, yielded a coefficient of 0.79. The overall 28-item instrument produced a Cronbach's Alpha coefficient of 0.82, indicating satisfactory internal consistency and supporting its suitability for use in the main study.

9.1 Characteristics of Pilot Study Respondents

To improve transparency concerning the source of the reliability coefficient, basic characteristics of the 30 pilot respondents should also be documented. This establishes that the pilot participants were reasonably similar to the stakeholder categories targeted in the main investigation.

Table 2

Demographic and Stakeholder Characteristics of Pilot Study Respondents (N = 30)

Variable	Category	Frequency	Percentage (%)
Stakeholder Category	Solar installer/technician	9	30.0
	Environmental/waste management personnel	6	20.0
	Regulatory agency personnel	5	16.7
	Solar energy users	10	33.3
	Total	30	100.0
Sex	Male	19	63.3
	Female	11	36.7
	Total	30	100.0
Age Group	20–29 years	6	20.0
	30–39 years	11	36.7
	40–49 years	8	26.7
	50 years and above	5	16.6
	Total	30	100.0
Years of Experience/Use of Solar Systems	Less than 2 years	5	16.7
	2–5 years	11	36.7
	6–10 years	9	30.0
	Above 10 years	5	16.6
	Total	30	100.0

Source: Pilot Survey.

Table 2 presents the characteristics of the respondents who participated in the pilot study. Of the 30 participants, 10 (33.3%) were solar energy users, 9 (30.0%) were solar installers or technicians, 6 (20.0%) were environmental or waste management personnel, while 5 (16.7%) were personnel of relevant regulatory agencies. This distribution ensured that the pilot test incorporated respondents representing the principal stakeholder groups covered by the main study.

In terms of sex, 19 respondents, representing 63.3%, were male, while 11 respondents, representing 36.7%, were female. With respect to age, the largest proportion of respondents, 11 (36.7%), were between 30 and 39 years, followed by 8 (26.7%) between 40 and 49 years. Six respondents (20.0%) were between 20 and 29 years, while 5 (16.6%) were aged 50 years and above.

Regarding experience with solar energy systems or related waste-management activities, 11 respondents (36.7%) had between two and five years of experience, while 9 (30.0%) had between six and ten years. Five respondents (16.7%) had less than two years of experience, while another 5 (16.6%) had more than ten years of experience. The distribution indicates that the pilot respondents possessed varying levels of exposure to solar energy and waste-management activities and were therefore considered appropriate for evaluating the clarity and internal consistency of the research instrument.

10. Method of Data Collection

The questionnaires were administered physically and electronically to respondents in Abuja. Research assistants helped in distribution and retrieval to improve response rate. Follow-up visits and reminders were used to ensure adequate return of completed questionnaires.

11. Method of Data Analysis

Data collected were analyzed using:

Descriptive statistics: frequency, percentage, mean, and standard deviation

Inferential statistics: Pearson Product Moment Correlation (PPMC) and multiple regression analysis

The Statistical Package for Social Sciences (SPSS) version 25 was used for analysis.

Decision rule:

1. Mean ≥ 3.0 = Agree / Accepted
2. Mean < 3.0 = Disagree / Rejected
3. Hypotheses were tested at 0.05 significance level.

12. Ethical Considerations

The study ensured:

1. Voluntary participation of respondents
2. Informed consent before data collection
3. Confidentiality and anonymity of responses
4. Use of data strictly for academic purposes
5. No harm or coercion of participants

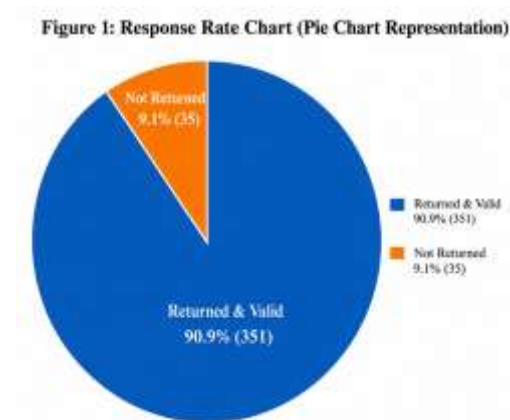
Results

1. Response Rate

Table 1: Questionnaire Response Rate

Response Category	Frequency	Percentage (%)
Returned & Valid	351	90.9
Not Returned	35	9.1
Total Distributed	386	100

Source: Field Survey 2026



Source: Field Survey 2026

The figure shows a high response rate indicating strong participation and reliability of the dataset.

2. Demographic Characteristics of Respondents

Table 2: Gender Distribution

Gender	Frequency	Percentage (%)
Male	212	60.4
Female	139	39.6
Total	351	100

Source: Field Survey 2026

Table 3: Category of Respondents

Category	Frequency	Percentage (%)
Solar Technicians/Installers	118	33.6
Solar Users (Households & Businesses)	146	41.6
Environmental Officers	41	11.7
Waste Management Personnel	46	13.1
Total	351	100

Source: Field Survey 2026

3. Research Question Analysis

Research Question 1: What are the current solar panel waste management practices in Abuja?

Table 4: Solar Panel Waste Management Practices

Item	Mean	Std. Dev	Decision
Solar panels are properly collected after damage/end-of-life	2.41	1.02	Disagree
There are designated recycling facilities for solar waste	2.18	0.98	Disagree
Informal recycling is commonly practiced	4.12	0.74	Agree
Solar waste is often mixed with general waste	3.89	0.81	Agree
Awareness of proper disposal methods is high	2.36	1.05	Disagree

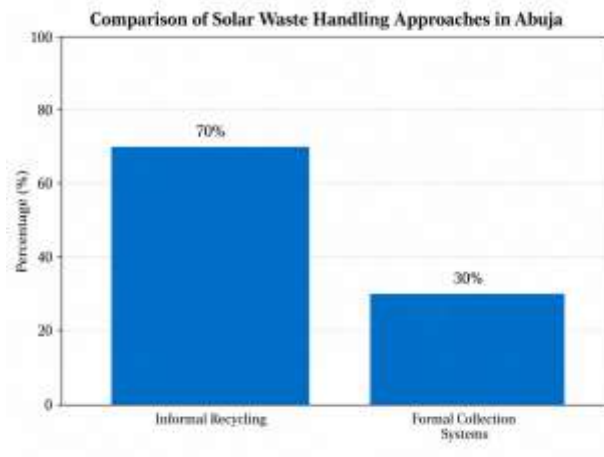
Source: Field Survey 2026

Cluster Mean = 3.00

Interpretation:

Findings show that solar panel waste management in Abuja is largely informal and poorly structured, with limited formal recycling systems and low awareness of proper disposal methods.

4.Waste Management Practice Trend



Research Question 2: What is the effect of solar panel waste management on environmental sustainability?

Table 5a

Response Distribution on Stakeholder Perceptions of Environmental Sustainability Implications (N = 351)

Item	Strongly Agree (5)	Agree (4)	Undecided (3)	Disagree (2)	Strongly Disagree (1)	Total
Poor solar waste disposal contributes to land pollution	122 (34.8%)	183 (52.1%)	44 (12.5%)	2 (0.6%)	0 (0.0%)	351 (100%)
Improper handling of solar waste may adversely affect groundwater quality	93 (26.5%)	166 (47.3%)	81 (23.1%)	11 (3.1%)	0 (0.0%)	351 (100%)

Recycling of solar components promotes resource conservation	139 (39.6%)	186 (53.0%)	26 (7.4%)	0 (0.0%)	0 (0.0%)	351 (100%)
Burning of solar components may contribute to air pollution	85 (24.2%)	157 (44.7%)	91 (25.9%)	17 (4.8%)	1 (0.3%)	351 (100%)
Effective solar waste management can enhance environmental sustainability	174 (49.6%)	162 (46.2%)	15 (4.3%)	0 (0.0%)	0 (0.0%)	351 (100%)

Source: Field Survey, 2026.

Table 5a presents the distribution of responses to the items assessing stakeholders' perceptions of the environmental implications of solar-panel waste management. For the statement that poor solar waste disposal contributes to land pollution, 122 respondents (34.8%) strongly agreed and 183 respondents (52.1%) agreed. Only 44 respondents (12.5%) were undecided, while 2 respondents (0.6%) disagreed.

Regarding the possible effect of improper solar-waste handling on groundwater quality, 93 respondents (26.5%) strongly agreed and 166 respondents (47.3%) agreed. Eighty-one respondents (23.1%) were undecided, while 11 respondents (3.1%) disagreed.

A substantial proportion of respondents also perceived recycling as beneficial to resource conservation. Specifically, 139 respondents (39.6%) strongly agreed and 186 respondents (53.0%) agreed that recycling solar components promotes resource conservation, while only 26 respondents (7.4%) were undecided.

On the perceived effect of burning solar components on air pollution, 85 respondents (24.2%) strongly agreed and 157 respondents (44.7%) agreed. Ninety-one respondents (25.9%) were undecided, 17 respondents (4.8%) disagreed, while 1 respondent (0.3%) strongly disagreed.

Finally, 174 respondents (49.6%) strongly agreed and 162 respondents (46.2%) agreed that effective solar waste management can enhance environmental sustainability. Only 15 respondents (4.3%) were undecided.

The response distributions provide the underlying frequencies from which the corresponding mean scores and standard deviations were obtained.

Table 5b

Descriptive Statistics on Stakeholder Perceptions of Environmental Sustainability Implications

Item	Mean	Std. Dev.	Decision
Poor solar waste disposal contributes to land pollution	4.21	0.67	Agree
Improper handling of solar waste may adversely affect groundwater quality	3.97	0.79	Agree
Recycling of solar components promotes resource conservation	4.32	0.61	Agree
Burning of solar components may contribute to air pollution	3.88	0.84	Agree
Effective solar waste management can enhance environmental sustainability	4.45	0.58	Agree
Grand Mean	4.17	—	Agree

Source: Field Survey, 2026.

Decision Rule: Mean $\geq$ 3.00 = Agree; Mean $<$ 3.00 = Disagree.

Table 5b shows that respondents generally perceived solar-panel waste management as having important implications for environmental sustainability. The highest mean score of 4.45 was recorded for the statement that effective solar waste management can enhance environmental sustainability. This was followed by the perception that recycling solar components promotes resource conservation, with a mean score of 4.32.

The statement that poor solar waste disposal contributes to land pollution recorded a mean score of 4.21, while improper handling of solar waste was perceived as potentially affecting groundwater quality, with a mean score of 3.97. The item relating to the burning of solar components and possible air pollution recorded the lowest mean score of 3.88, although this was still above the criterion mean of 3.00.

The grand mean of 4.17 indicates that respondents generally agreed that inadequate management of solar-panel waste may have adverse environmental implications and that appropriate recycling and waste-management practices may contribute to environmental sustainability.

However, these findings represent stakeholder perceptions rather than directly measured environmental outcomes. The study did not undertake laboratory measurements of soil

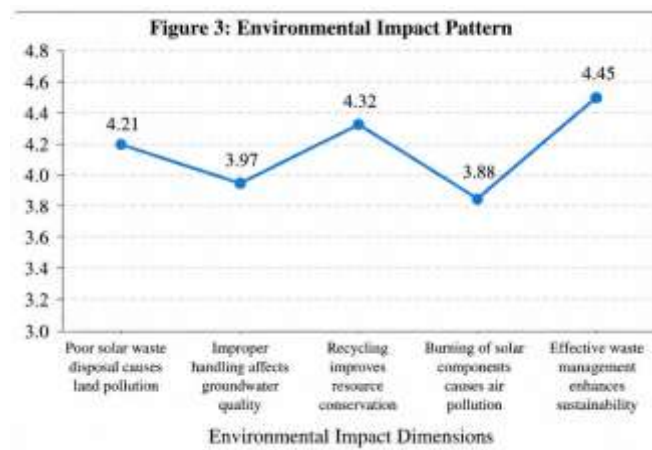
contamination, groundwater quality, air pollutants, waste quantities, actual recycling rates, or life-cycle emissions. Consequently, the results should be interpreted as respondents' assessment of perceived environmental risks and sustainability benefits associated with solar-panel waste-management practices.

Cluster Mean = 4.17

Interpretation:

Respondents generally perceived poor solar-panel waste management as a threat to environmental sustainability, with an overall mean of 4.17. They also viewed effective waste management and recycling as important for reducing perceived pollution risks and conserving resources.

Figure 3: Environmental Impact Pattern



Source: Field Survey 2026

5. Research Question 3: What challenges affect solar panel waste management in Abuja?

Table 6: Challenges of Solar Panel Waste Management

Item	Mean	Std. Dev	Decision
Lack of recycling infrastructure	4.48	0.55	Agree
Weak government enforcement	4.21	0.72	Agree
Low public awareness	4.09	0.81	Agree
High cost of recycling processes	3.94	0.88	Agree
Limited technical expertise	3.87	0.91	Agree

Source: Field Survey 2026

Cluster Mean = 4.12

Interpretation:

The findings reveal that inadequate infrastructure and weak policy enforcement are the major constraints affecting solar panel waste management in Abuja.

6. Test of Hypothesis

Hypothesis

H₀: Solar panel waste management has no significant impact on environmental sustainability in Abuja.

A Pearson Product Moment Correlation analysis was conducted.

Table 7: Correlation Analysis

Variables	r-value	p-value	Decision
Waste Management vs Environmental Sustainability	0.74	0.000	Significant

Source: Field Survey 2026

Interpretation:

Since the p-value (0.000) is less than 0.05, the null hypothesis is rejected. This indicates that solar panel waste management has a significant positive impact on environmental sustainability in Abuja.

7. Summary of Findings

The key findings from the study include:

1. Solar panel waste management in Abuja is largely informal.
2. There is limited availability of recycling infrastructure.
3. Poor waste handling contributes to environmental pollution.
4. Effective waste management improves sustainability outcomes.

There is a strong and significant relationship between waste management and environmental sustainability.

Discussion of Findings

1. Solar Panel Waste Management Practices in Abuja

The findings show that solar panel waste management in Abuja is largely informal and poorly structured. Respondents disagreed that damaged or end-of-life solar panels are properly collected ($M = 2.41$, $SD = 1.02$), that designated recycling facilities are available ($M = 2.18$, $SD = 0.98$), and that awareness of proper disposal methods is high ($M = 2.36$, $SD = 1.05$). In contrast, informal recycling ($M = 4.12$, $SD = 0.74$) and mixing solar waste with general waste ($M = 3.89$, $SD = 0.81$) were widely reported.

This pattern may be explained by the fact that solar adoption has expanded faster than the infrastructure and regulatory systems required to manage end-of-life components. In the absence of accessible formal collection points and specialized recycling facilities, households, businesses, and technicians may rely on informal recyclers. This agrees with All On and Deloitte (2022) and John, Okorhi, and Uhunmwangho (2023), who identified weak recycling infrastructure, informal handling, and regulatory limitations in Nigeria.

Compared with more developed photovoltaic markets, where producer responsibility, formal collection, and specialized recycling systems are increasingly established, Abuja still appears to lack an integrated end-of-life management structure. The finding therefore reflects a broader gap between solar-energy expansion and waste-governance development.

2. Solar Panel Waste Management and Perceived Environmental Sustainability

Respondents generally perceived solar-panel waste management as having important implications for environmental sustainability, with a grand mean of 4.17. The strongest agreement was that effective waste management can enhance environmental sustainability ($M = 4.45$, $SD = 0.58$), followed by the view that recycling promotes resource conservation ($M = 4.32$, $SD = 0.61$).

Respondents also associated poor disposal with land pollution ($M = 4.21$, $SD = 0.67$), improper handling with possible groundwater contamination ($M = 3.97$, $SD = 0.79$), and burning of solar components with possible air pollution ($M = 3.88$, $SD = 0.84$). These perceptions are consistent with the circular-economy perspective emphasized by Umar, Ahmed, and Rana (2025) and Chowdhury et al. (2024), which highlights the value of recovering reusable materials rather than treating photovoltaic equipment only as waste.

The findings also align with UNEP (2024), which identifies uncontrolled e-waste processing and informal burning as environmental and health concerns in developing countries. Similarly, Wambach, Libby, and Shaw (2024) emphasize that effective photovoltaic recycling can reduce material losses and environmental burdens.

However, these results represent stakeholder perceptions rather than direct measurements of environmental conditions. The study did not measure soil contamination, groundwater quality, air emissions, waste quantities, actual recycling rates, or life-cycle emissions. Therefore, the findings should not be interpreted as proof that specific environmental contamination has occurred in Abuja.

3. Challenges Affecting Solar Panel Waste Management

The major challenges identified were lack of recycling infrastructure ($M = 4.48$, $SD = 0.55$), weak government enforcement ($M = 4.21$, $SD = 0.72$), low public awareness ($M = 4.09$, $SD = 0.81$), high recycling costs ($M = 3.94$, $SD = 0.88$), and limited technical expertise ($M = 3.87$, $SD = 0.91$). The cluster mean of 4.12 shows that respondents considered these challenges substantial.

The absence of adequate recycling infrastructure helps explain the continued reliance on informal disposal channels. Weak enforcement may also create a gap between existing environmental regulations and actual practices. This is consistent with NESREA (2022), which provides a regulatory framework for electronic-waste management, but the findings suggest that implementation remains a concern.

Low awareness may further encourage users to dispose of solar equipment with general waste, while high recycling costs and limited technical expertise can discourage investment in formal recovery systems. These challenges are therefore interconnected and collectively reinforce informal waste-management practices.

4. Relationship Between Waste Management and Perceived Environmental Sustainability

The Pearson correlation analysis produced $r = 0.74$ with $p < 0.001$, indicating a strong and statistically significant relationship between solar-panel waste management and perceived environmental sustainability. The null hypothesis was therefore rejected.

However, this result demonstrates an association rather than causation. Because the study is cross-sectional and the sustainability variable is perception-based, it cannot establish that better waste-management practices directly cause improved environmental conditions.

The finding nevertheless supports Life Cycle Assessment and Circular Economy perspectives, which emphasize that environmental sustainability depends partly on how products are managed at the end of their useful life. Wambach et al. (2024) and Chowdhury et al. (2024) similarly stress the importance of recycling, recovery, and responsible end-of-life treatment.

5. Implications for Environmental Sustainability

The findings imply that the environmental benefits of solar-energy adoption may be weakened if end-of-life equipment is not properly managed. Solar panels, batteries, inverters, cables, and related components will eventually become waste, making collection, reuse, refurbishment, recycling, and safe disposal essential parts of sustainable solar development.

The findings support the Life Cycle Assessment perspective by showing that sustainability must consider the entire product lifecycle, not only the electricity-generation stage. They also support Circular Economy Theory by emphasizing material recovery, reuse, and recycling, and Extended Producer Responsibility by highlighting the need for manufacturers, importers, distributors, installers, regulators, and consumers to share responsibility for end-of-life products.

Conclusion

The study found that solar-panel waste management in Abuja is mainly informal, with limited formal collection and recycling infrastructure, low awareness, and frequent mixing of solar waste with general waste. Respondents perceived poor waste management as presenting environmental risks, while recycling and effective disposal were viewed as beneficial to resource conservation and sustainability.

A strong and statistically significant relationship was found between solar-panel waste management and perceived environmental sustainability ($r = 0.74$, $p < 0.001$). However, this relationship should be interpreted as an association rather than proof of causation, and the environmental findings represent stakeholder perceptions rather than direct environmental measurements.

The major constraints identified were inadequate recycling infrastructure, weak regulatory enforcement, low public awareness, high recycling costs, and limited technical expertise. The study therefore concludes that sustainable expansion of solar energy in Abuja requires corresponding development of effective end-of-life waste-management systems.

Recommendations

1. **Establish dedicated solar-waste collection and recycling systems** to prevent end-of-life components from entering general waste streams.
2. **Strengthen regulatory enforcement and monitoring** by NESREA, AEPB, and other relevant agencies.
3. **Implement Extended Producer Responsibility schemes** requiring manufacturers, importers, and distributors to support take-back and recycling programmes.

4. **Increase public and stakeholder awareness** on safe disposal, recycling, and environmental risks associated with improper handling.
5. **Invest in recycling and material-recovery infrastructure** for valuable materials such as aluminium, copper, and silicon-containing components.
6. **Provide technical training** for installers, technicians, waste handlers, and recyclers on safe dismantling, storage, transportation, and recycling.
7. **Integrate informal recyclers into formal waste-management systems** through registration, training, and links with licensed recycling facilities.
8. **Promote circular-economy practices**, including repair, reuse, refurbishment, and recycling before final disposal.
9. **Develop a solar-waste data and tracking system** to monitor equipment entering the market and reaching end-of-life.
10. **Conduct future studies using objective environmental measurements**, including waste quantities, recycling rates, soil and groundwater quality, material-recovery efficiency, and life-cycle environmental impacts.

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