


From Adoption to Sustainability: Prospects and Barriers to Maintaining Clean Technologies in Nigeria's Smallholder Farming Ecosystems

Sani Abubakar Mashi ^{1,*}, Nenadi Rehab Oluyori¹ and Obaro Dominic Oghenejabor²

¹Department of Geography, Faculty of Geographical and Atmospheric Sciences, University of Abuja, PMB 117, Abuja, Nigeria; E-mail: abubakar.sani@uniabuja.edu.ng

²Department of Environmental Management, Delta State University of Science & Technology, Ozoro, Nigeria



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ABSTRACT: Smallholder farming systems are central to food production, rural livelihoods, and socio-economic stability in the Global South, yet their productivity and resilience are increasingly threatened by soil degradation, inefficient resource use, energy deficits, and climate-induced shocks. Clean technologies—spanning resource management, renewable energy, and environmental protection—offer potential to enhance productivity, reduce emissions, and strengthen resilience. However, evidence on their long-term maintenance, durability, and embedding within smallholder systems remains limited, and existing research often treats sustainability as an outcome of adoption rather than a staged socio-technical process. Addressing this gap, the study advances and empirically applies the Clean Technology Maintenance and Embedding Framework (CTMEF) in Nigerian smallholder agriculture, examining how technical robustness, institutional support, financial continuity, and market integration interact to shape maintenance performance and embedding outcomes. The findings indicate that sustainability is structurally constrained: technologies achieve durable embedding only when multiple enabling conditions are simultaneously strong, whereas high technical complexity in the absence of adequate institutional and financial support significantly increases the risk of failure. The study's novelty lies in integrating cross-domain technologies within a unified framework, operationalizing threshold-based and multiplicative dynamics, and providing empirically grounded insights from a Global South context. These results inform actionable strategies—including participatory capacity building, institutional strengthening, policy alignment, and innovative financing—to enhance the durability, scalability, and transformative potential of clean technologies, advancing both theoretical understanding and practical guidance for resilient, low-carbon smallholder agricultural systems.

Keywords: Clean technology, Smallholder farming, Renewable energy, Resource efficiency, Environmental sustainability, Nigeria.

1. INTRODUCTION

Smallholder farming systems are central to agricultural production, food security, and rural livelihoods across the Global South. They supply over 80% of national food demand and employ a substantial proportion of rural populations, making them critical for socio-economic stability and poverty reduction [1, 2]. These systems are typically characterized by small and fragmented landholdings, heavy reliance on rain-fed agriculture, limited access to mechanization and modern inputs, and

strong dependence on local natural resources [2]. However, their sustainability is increasingly threatened by environmental degradation, declining soil fertility, inefficient energy use, water scarcity, and climate-induced shocks such as droughts and floods [3]. These

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pressures undermine productivity and resilience while intensifying greenhouse gas emissions, biodiversity loss, and land degradation.

Clean technologies—innovations that reduce environmental impacts, enhance resource-use efficiency, and promote renewable and low-carbon energy—have emerged as promising pathways for strengthening sustainability in smallholder systems [4, 5]. These include solar-powered irrigation and processing systems, improved biomass and biogas technologies, climate-smart agricultural practices, water-efficient tools, organic and bio-based inputs, and waste-to-resource innovations such as composting and biofertilizer production. When effectively implemented, such technologies can enhance productivity, reduce emissions, strengthen climate resilience, and support inclusive rural development [6-9].

Despite increasing policy attention and numerous pilot initiatives, many clean technology interventions fail to achieve long-term functionality or durable system integration [10-14]. Existing research has predominantly concentrated on adoption drivers, behavioral intentions, or short-term technical performance, with limited attention to maintenance durability, institutional alignment, and structural embedding processes [15-18]. As noted by Yin *et al.* [2], multi-actor cooperation—including governments, enterprises, and farmers—is critical for rural energy transitions, while Yin and Yuan [15] demonstrate that technological capacity and economic conditions significantly shape rural energy–economy–environment (3E) systems. However, the broader clean technology literature remains fragmented across domains (resource management, energy access, environmental protection) and often treats sustainability as an outcome of individual adoption decisions rather than a staged socio-technical process shaped by institutional density, financial continuity, market integration, and technical robustness.

A significant gap, therefore, exists in understanding how clean technologies transition from initial adoption to sustained maintenance and eventual embedding within smallholder systems. Few studies conceptualize sustainability as a condition-dependent, structurally patterned process operating across multiple interacting domains. Moreover, limited empirical research has undertaken cross-technology comparisons within a unified analytical framework capable of systematically explaining why some technologies achieve durable embedding while others deteriorate or are ultimately abandoned. This gap constrains both theoretical advancement and practical guidance for scaling clean

technologies in resource-constrained agricultural contexts.

To address this gap, this study advances and empirically applies the Clean Technology Maintenance and Embedding Framework (CTMEF), which conceptualizes sustainability as a staged socio-technical process: (1) adoption, (2) maintenance performance, and (3) system embedding. The framework integrates technical robustness, institutional support density, financial continuity mechanisms, and market integration as interacting structural determinants of durability. Rather than treating sustainability as additive or purely behavioral, the study examines threshold-based and multiplicative dynamics that shape long-term embedding outcomes. The overarching research question guiding this study is:

How do structural socio-technical conditions influence the maintenance performance and long-term embedding of clean technologies within Nigerian smallholder farming systems?

The specific objectives are to:

1. Systematically review and classify major clean technology categories applied in Nigeria's smallholder farming systems across resource management, energy, and environmental protection domains;
2. Develop and operationalize the CTMEF, identifying and measuring key structural variables influencing maintenance sustainability;
3. Empirically assess maintenance performance and embedding probability using comparative and threshold-based analysis across technology categories; and
4. Derive policy-relevant strategic pathways for strengthening institutional coordination, financing mechanisms, market integration, and participatory capacity building to enhance durability and scalable system embedding.

By shifting the analytical focus from short-term adoption to maintenance durability and structural embedding, and by integrating cross-domain technologies within a unified socio-technical framework, this study contributes theoretical advancement and empirically grounded insights from Nigeria's smallholder context. It thereby extends understanding of sustainability transitions in resource-constrained agricultural systems while offering operational guidance for designing resilient, low-carbon,

and institutionally supported clean technology ecosystems.

Nigeria is a particularly good testing ground for conducting a study with the above objectives. While the country has a regional variation in climate and infrastructure, smallholder farmers are largely similar in operating under low-resource, subsistence conditions with limited access to mechanization, modern inputs, and technical support. These shared socio-technical constraints - such as weak institutional support and restricted financing - apply across agro-ecological zones, making the study's findings on clean technology maintenance and embedding broadly relevant. Minor regional differences, like rainfall or market access, are acknowledged but do not substantially alter the overall patterns or recommendations.

2. CONCEPTUAL FRAMEWORK: CLEAN TECHNOLOGY IN SMALLHOLDER FARMING SYSTEMS

Clean technology in agriculture encompasses innovations, practices, and systems that enhance productivity while minimizing environmental degradation and supporting socio-economic sustainability [6, 19]. In

smallholder farming systems, clean technologies must respond to highly constrained conditions, including limited capital, weak infrastructure, fluctuating climatic conditions, and a strong reliance on local ecological resources [3, 20, 21]. Consequently, for clean technologies to be effective and sustainable in smallholder contexts, they must be affordable, adaptable to diverse agro-ecological settings, low-maintenance, and compatible with indigenous knowledge and farming practices. Unlike large-scale commercial agriculture, where technological sustainability is often driven by financial capacity and technical specialization, the sustainability of clean technologies in smallholder systems depends on a broader set of interacting factors. Technical efficiency alone is insufficient. Long-term functionality is shaped by institutional support structures, access to markets and spare parts, availability of extension services, policy incentives, and the willingness of farmers to adopt, maintain, and integrate new technologies into existing livelihood systems. Behavioral acceptance, trust in technology providers, and perceived benefits relative to traditional practices play a critical role in determining whether clean technologies are maintained or abandoned over time [12, 22-25].

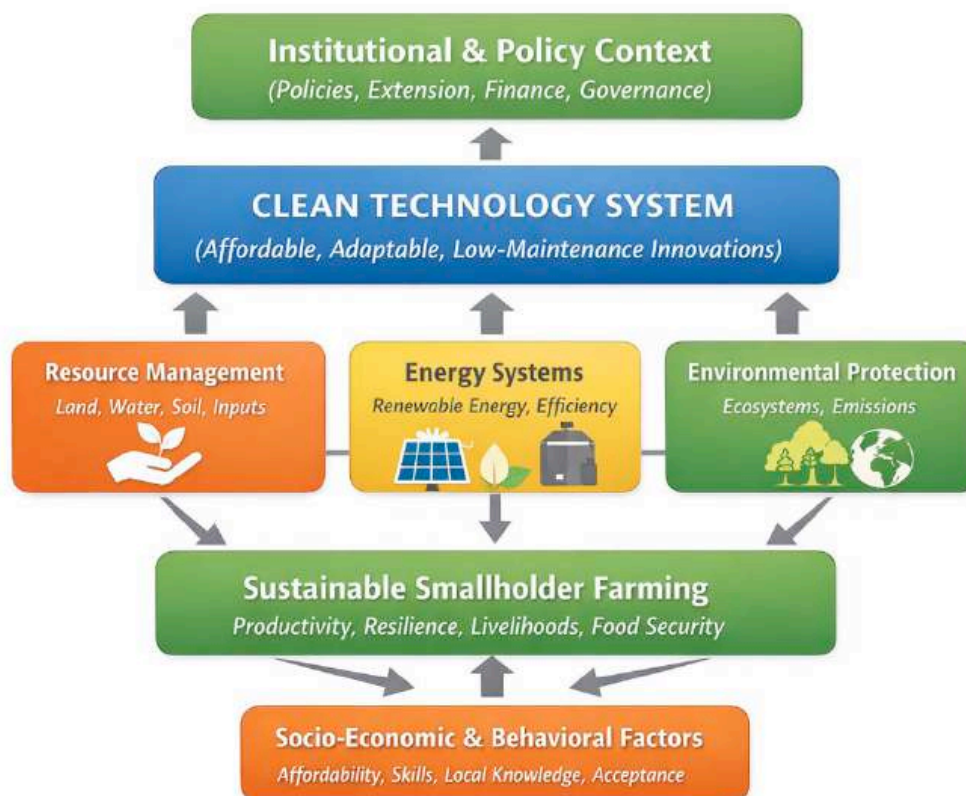


Figure 1: Conceptual framework for clean technology sustainability in smallholder farming systems.

The resource–energy–environment nexus provides a useful lens for understanding the role of clean technologies in smallholder farming ecosystems [7, 18]. Typically, smallholder agriculture is deeply embedded within this nexus, as farm productivity relies directly on land, water, biomass, and energy resources. Inefficient resource use - such as poor soil management, unsustainable fuelwood harvesting, and wasteful water use - intensifies environmental degradation and undermines long-term agricultural productivity. At the same time, limited access to modern energy services constrains irrigation, processing, storage, and value addition, reinforcing poverty and vulnerability [9].

Clean technologies operate at the intersection of this resource–energy–environment nexus. Resource-efficient technologies, such as soil conservation practices, organic amendments, and water-saving irrigation systems, reduce pressure on land and water resources [9, 16]. Renewable and low-carbon energy technologies, including solar-powered irrigation, improved cookstoves, and biogas systems, enhance energy access while reducing dependence on fossil fuels and unsustainable biomass use [3, 21]. Environmental protection technologies and practices, such as agroforestry, waste recycling, and climate-smart agriculture, contribute to ecosystem restoration, emission reduction, and climate resilience [14].

The conceptual framework underpinning this study recognizes clean technology sustainability as a socio-technical system, where outcomes emerge from the interaction between technological attributes, socio-economic conditions, institutional arrangements, and environmental feedback. When enabling conditions such as supportive policies, functional institutions, access to finance, and farmer capacity building are present, clean technologies can generate positive feedback loops that enhance resource efficiency, improve energy access, protect the environment, and strengthen rural livelihoods. Conversely, weak institutions, poor maintenance capacity, and limited market integration can disrupt these feedbacks, leading to technology failure and dis-adoption [5]. By situating clean technologies within the resource–energy–environment nexus and the realities of smallholder farming systems, this framework highlights the importance of moving beyond deployment-focused approaches toward integrated strategies that prioritize maintenance, system compatibility, and long-term sustainability. This perspective is particularly relevant for Nigeria, where clean technology interventions must address not only environmental goals but also poverty reduction, food security, and rural development objectives simultaneously.

Figure 1 illustrates the integrative role of clean technologies in advancing sustainable smallholder farming systems through the interconnected resource–energy–environment nexus. At the core of the framework is the clean technology system, comprising affordable, adaptable, and low-maintenance innovations that are influenced by the surrounding institutional and policy context, including governance structures, extension services, and financial mechanisms. Clean technologies interact with three key domains - resource management, energy systems, and environmental protection - highlighting their role in improving land, water, and soil use efficiency; expanding access to renewable and efficient energy; and reducing emissions while conserving ecosystems. The combined effects of these domains contribute to sustainable smallholder farming outcomes, such as enhanced productivity, resilience, livelihoods, and food security. Socio-economic and behavioral factors, including affordability, skills, local knowledge, and user acceptance, provide critical feedback that shapes technology performance, maintenance, and long-term sustainability.

■ 3. METHODOLOGY

■ 3.1. Study Design and Analytical Orientation

This study adopts a structured, model-driven evidence synthesis approach designed to approximate explanatory empirical modeling within the constraints of secondary data. Rather than conducting a descriptive literature review, we develop and operationalize a theory-informed analytical model - the CTMEF - to explain variation in maintenance performance and long-term sustainability outcomes across clean technologies deployed in Nigerian smallholder farming systems.

The analytical objective is explanatory rather than descriptive: specifically, to identify which structural variables most strongly predict sustained functionality beyond initial adoption. Conceptually, the study treats maintenance continuity as the dependent outcome variable, and socio-technical, institutional, financial, and market characteristics as explanatory variables. This reframing allows for structured cross-case comparison and patterned inference, thereby strengthening analytical rigor beyond narrative synthesis.

The research design integrates:

1. Structured literature identification and case selection
2. Construct operationalization

3. Comparative qualitative scoring
4. Cross-case pattern analysis
5. Expert validation

This multi-step approach enhances internal consistency by ensuring that each stage of the analysis - case selection, construct definition, variable coding, index construction, and cross-case comparison - is logically connected and guided by the same underlying conceptual framework. Because the analytical procedures are applied systematically across all cases, the risk of ad hoc interpretation or selective emphasis is reduced. At the same time, the approach improves inferential transparency by clearly documenting how conclusions are derived from the data. Each analytical step is explicitly described, including how variables were operationalized, how scores were assigned, and how patterns were interpreted. This allows readers to trace the reasoning process from evidence to findings, evaluate the robustness of the interpretations, and, if desired, replicate or adapt the framework in other contexts.

The study conceptualizes clean technologies as embedded within smallholder farming ecosystems and influenced by interactions among technical, behavioral, institutional, and environmental factors. The analytical framework was integrated:

- Technical analysis: assessment of design, durability, and maintenance requirements of clean technologies.
- Socio-economic analysis: evaluation of affordability, farmer capacity, local knowledge, and behavioral acceptance.
- Institutional and policy analysis: review of governance structures, extension support, financing mechanisms, and policy incentives.
- Environmental analysis: consideration of impacts on land, water, energy use, and greenhouse gas emissions.

By linking these dimensions, the framework facilitates identification of both barriers and enabling conditions that influence the long-term sustainability of clean technologies in smallholder farming.

To enhance the reliability and applicability of the findings, expert consultation was conducted with:

- Agricultural extension officers and field practitioners in Nigeria.

- Researchers specializing in renewable energy, sustainable agriculture, and environmental management.
- Policy makers and project implementers involved in smallholder technology interventions.

Expert insights were systematically incorporated at the validation stage to strengthen the credibility and practical relevance of the findings. Agricultural extension officers, renewable energy specialists, and policy practitioners were consulted to assess whether the identified patterns accurately reflected field realities and operational experiences. Their feedback helped verify the plausibility of the observed relationships among variables in the comparative analysis, particularly regarding maintenance bottlenecks, institutional support gaps, and financing constraints. In addition, expert consultation served as a mechanism for identifying contextual nuances and overlooked factors that may not have been fully captured in the documentary evidence, such as informal repair networks, seasonal labor constraints, or locally adaptive maintenance practices. Where such insights revealed inconsistencies or gaps, the analytical interpretation was refined accordingly. The expert input informed the translation of analytical findings into actionable recommendations. By grounding policy suggestions in practitioner experience, the study ensures that proposed interventions - such as strengthening extension density, developing localized repair ecosystems, or aligning financing mechanisms with agricultural income cycles - are not only theoretically sound but also operationally feasible within Nigeria's smallholder farming context.

■ 3.2. Data Sources and Selection Criteria

The study draws on secondary data from:

- Peer-reviewed articles on clean technologies, renewable energy, sustainable agriculture, and resource management in smallholder contexts.
- Policy and technical reports from Nigerian institutions (e.g., Federal Ministry of Agriculture and Rural Development, Nigerian Energy Commission, environmental agencies).
- International reports from FAO, UNEP, World Bank, and CGIAR, providing insights on innovation, best practices, and policy frameworks.
- Case studies of clean technology interventions in Nigerian smallholder communities, including pilot projects and scaling initiatives.

Inclusion criteria: English-language publications from 2020–2025, with explicit focus on smallholder systems and evidence on resource efficiency, renewable energy adoption, environmental protection, or socio-economic sustainability. Exclusion criteria: industrial-scale agriculture or studies lacking empirical insight on maintenance or long-term functionality.

■ 3.3. Data Extraction and Synthesis

A structured extraction template captured:

- Types and functions of clean technologies in resource, energy, and environmental management.
- Technical attributes influencing performance and maintenance.
- Socio-economic and behavioral factors affecting adoption and continued use.
- Institutional, policy, and market conditions shaping sustainability and scalability.
- Reported outcomes and lessons learned from case studies.

Data were analyzed using thematic content analysis guided by the conceptual framework (Figure 1). Themes were organized across the resource–energy–environment nexus, identifying cross-cutting factors that influence maintenance, durability, and long-term embedding of clean technologies. This approach ensures that all questionnaire items and analytic categories are directly tied to theoretical constructs and prior evidence, enabling systematic comparison of technologies, challenges, and enabling conditions across multiple smallholder contexts.

By linking theoretical constructs (e.g., behavioral intention, facilitating conditions, and adoption outcomes as highlighted by Yin *et al.* [16] to observed factors in Nigerian smallholder contexts, the methodology ensures that the analysis is both theory-informed and empirically grounded, providing actionable insights into mechanisms that support sustainable clean technology systems

■ 3.4. Model Development: Clean Technology Maintenance and Embedding Framework (CTMEF)

The CTMEF builds upon behavioral adoption theories such as UTAUT2, drawing on insights from Yin *et al.* [16], who used the Unified Theory of Technology Acceptance and Use (UTAUT2) and structural equation modeling (SEM) to examine clean energy adoption in rural China,

but extends them by introducing maintenance performance as an intermediate outcome between adoption and system embedding. Whereas adoption models typically treat behavioral intention and facilitating conditions as predictors of use, this study posits that:

Adoption is a necessary but insufficient condition for sustainability.

The framework, therefore, specifies a three-stage process:

1. Adoption (initial uptake)
2. Maintenance performance (operational continuity over time)
3. System embedding (institutional and market integration)

Maintenance performance is treated as the central mediating variable influencing embedding probability. Six explanatory constructs were operationalized as independent analytical variables:

- Technical Robustness (TR): durability, modularity, spare-part dependency
- User Capacity Intensity (UCI): level of skill required for operation and repair
- Institutional Support Density (ISD): frequency and reliability of extension and repair networks
- Financial Continuity Mechanisms (FCM): presence of credit, PAYG, cooperative financing
- Market Integration Strength (MIS): degree of linkage to income-generating value chains
- Environmental Compatibility (EC): agro-ecological suitability

Each construct was coded qualitatively on a three-point ordinal scale (Low = 1, Medium = 2, High = 3) to enable structured comparative modeling.

This multi-factor conceptualization enables a structured analytical approach comparable to prior applications of UTAUT2 and structural equation modeling (SEM) in rural energy research, where behavioral intention, facilitating conditions, and actual use are systematically linked to observed outcomes. However, unlike studies that concentrate primarily on explaining initial adoption, our framework extends the analytical scope by explicitly integrating maintenance performance, technical durability, and system integration as mediating processes. By positioning these factors between

adoption and long-term sustainability, the framework captures the dynamic processes that determine whether clean technologies remain functional and embedded over time, thereby providing a more comprehensive explanation of sustained performance.

■ 3.5. Case Selection and Data Structure

A total of 28 clean technology interventions implemented between 2020–2025 were selected based on:

- Evidence of deployment in Nigerian smallholder systems
- Documentation extending beyond pilot installation
- Availability of information on operational performance

Cases were grouped into three categories:

- Resource management technologies (n = 10)
- Energy technologies (n = 9)
- Environmental protection technologies (n = 9)

For each case, construct scores were assigned using documented evidence. Observed maintenance outcome (MO) was coded as:

- 1 = High discontinuity/abandonment
- 2 = Partial continuity
- 3 = Sustained functionality

This process generated a systematically coded comparative dataset in which each case was assessed using the same set of clearly defined variables and ordinal scoring criteria. Because all interventions were evaluated against identical analytical dimensions, the resulting dataset allowed for consistent comparison across technologies and contexts. This structure made it possible to move beyond isolated case descriptions and instead identify recurring patterns, contrasts, and conditional relationships across cases. In turn, this facilitated cross-case inference - enabling the study to draw reasoned conclusions about which combinations of technical, institutional, and financial factors are most strongly associated with sustained maintenance performance in Nigerian smallholder systems.

To enhance methodological rigor and reduce potential bias, this study adopted a PRISMA-informed systematic review approach to guide literature identification, screening, eligibility assessment, and inclusion. A structured search strategy was implemented across

multiple academic databases using clearly defined keyword combinations related to clean technologies, smallholder agriculture, maintenance, institutional support, and sustainability transitions. Explicit inclusion and exclusion criteria were applied to ensure relevance, methodological transparency, and empirical grounding. Only peer-reviewed studies and high-quality institutional reports with clearly described research designs, adequate data reporting, and analytical consistency were retained. Each selected study was subjected to a structured quality appraisal evaluating clarity of research design, sample adequacy, analytical rigor, internal consistency, and transparency in reporting limitations, and was subsequently classified according to its methodological strength. To mitigate publication and sectoral bias, the review integrated evidence across resource management, energy, and environmental protection domains and included both supportive and critical findings. These procedures ensured transparency, replicability, and reliability of the evidence base underpinning the analytical framework and subsequent comparative and threshold-based assessments.

■ 3.6. Maintenance Sustainability Index (MSI) construction

To synthesize explanatory variables into a comparative performance metric, we developed a composite Maintenance Sustainability Index (MSI), defined analytically as:

$$MSI = (TR + ISD + FCM + MIS + EC) - UCI$$

Where:

- Higher TR, ISD, FCM, MIS, and EC increase predicted sustainability
- Higher UCI (complexity burden) reduces predicted sustainability

The MSI therefore functions as a structured additive model approximating multi-variable interaction effects. Although not a statistical regression model, this structured scoring approach enables:

- Ranking of cases
- Identification of threshold patterns
- Detection of variable clustering effects
- Cross-category mean comparison

This methodological approach enhances the study's analytical rigor and empirical transparency by

systematically operationalizing key constructs, applying structured comparative scoring, and making explicit the relationships between explanatory variables and observed outcomes. By clearly defining how cases were selected, how variables were coded, and how the composite index was constructed, the approach reduces subjectivity and improves the reproducibility of the analysis. At the same time, it remains appropriately aligned with the qualitative nature of the available data, which are drawn from documented case studies and policy reports rather than primary quantitative surveys. Rather than overstating precision, the framework uses ordinal scoring and structured comparison to identify directional patterns and conditional relationships, thereby generating analytically robust insights while respecting the evidentiary constraints of secondary qualitative sources.

■ 4. RESULTS AND DISCUSSION

■ 4.1. Categories of Clean Techniques Utilized

Table 1 presents a thematic analysis identifying three interconnected categories of clean technologies in Nigerian smallholder farming—resource management, energy, and environmental protection—highlighting their integrated role within the resource–energy–environment nexus [26]. Resource management technologies enhance land, water, and soil sustainability through climate-smart agriculture (CSA) practices such as reduced tillage, cover cropping, crop rotation, and intercropping, which improve soil organic matter, moisture retention, erosion control, and climate resilience [27-29]. Agroforestry systems incorporating nitrogen-fixing and fruit trees strengthen soil fertility and microclimate

regulation while diversifying outputs [30]. Drip and sprinkler irrigation improve water-use efficiency in water-scarce areas [25], and organic inputs such as compost, biochar, and green manures restore soil nutrients and reduce reliance on synthetic fertilizers [31, 32]. Energy technologies address farm-level energy deficits and emissions, including solar-powered irrigation for off-grid water access [33], biogas digesters that convert waste into energy and nutrient-rich slurry [26, 32], improved cookstoves that reduce fuelwood use and indoor pollution [34, 35], and solar dryers that reduce post-harvest losses and increase income [25]. Environmental protection technologies promote ecosystem conservation and climate adaptation through Integrated Pest Management (IPM) to reduce pesticide use [36-38], soil and water conservation structures to control erosion, agroforestry and tree planting for carbon sequestration and biodiversity benefits, and waste recycling and composting to close nutrient loops and reduce pollution [39].

Together, resource management, energy, and environmental protection technologies create an integrated system that enhances productivity, reduces environmental degradation, improves climate resilience, and supports sustainable smallholder farming. The findings underscore the importance of context-specific, coordinated approaches to clean technology adoption and maintenance in Nigeria.

■ 4.2. Challenges in the Utilization of Clean Technologies

The thematic analysis of challenges affecting clean technology utilization in Nigerian smallholder systems (Table 2) identifies four interrelated constraint categories—technical, socio-economic, institutional, and

Table 1: Thematic summary of clean technology categories, associated benefits, and regional evidence base.

Category	Key Technologies / Practices	Primary Benefits	Illustrative Nigerian Case Examples (Region)	Key References
Resource Management	Climate-smart agriculture (CSA), agroforestry, water-efficient irrigation, and organic fertilizers	Improved soil fertility, optimized water use, enhanced yields, and climate resilience	CSA trials in Northern Nigeria (semi-arid savannah zone); agroforestry systems in Benue State (Middle Belt agro-ecology)	[30]
Energy Technologies	Solar irrigation pumps, biogas digesters, improved cookstoves, solar dryers	Reduced emissions, improved energy reliability, enhanced agro-processing efficiency	Solar-powered irrigation in Kaduna State (North-West); smallholder biogas systems in Oyo State (South-West)	[23]
Environmental Protection	Integrated Pest Management (IPM), soil and water conservation, tree planting, composting	Ecosystem restoration, emission reduction, biodiversity conservation, resilience strengthening	IPM adoption in Kano State (Sudan savannah zone); composting initiatives in Plateau State (Middle Belt highlands)	[37]

Note: Technologies and case examples were synthesized from peer-reviewed empirical studies and institutional reports covering Nigeria's major agro-ecological zones (northern savannah, Middle Belt, and southern regions). Citations correspond to representative studies informing each category.

Table 2: Thematic summary of challenges affecting clean technology maintenance, with an evidentiary basis.

Challenge Category	Specific Issues Identified in Literature	Implications for Maintenance and Sustainability	Representative Evidence Base (Regional Coverage)	References
Technical	Complex system designs, limited durability, lack of spare parts, and repair services	Increased malfunction rates, higher abandonment risk, and reduced continuity	Evidence from solar irrigation, biomass, and mechanized systems across northern and central Nigeria	[26,28,39]
Socio-Economic	High upfront costs, limited technical skills, and cultural resistance to innovation	Reduced sustained usage, inconsistent maintenance practices	Smallholder studies across multiple Nigerian regions highlight affordability and skill constraints	[35,47,50]
Institutional	Weak extension services, fragmented coordination, and insufficient training support	Limited access to repairs, poor follow-up monitoring, and low institutional density	Empirical evidence from rural development and agricultural extension assessments	[31,34,42]
Policy & Market	Inconsistent policy incentives, unstable subsidy programs, and weak input/output market linkages	Constrained scaling, reduced long-term viability, and financial discontinuity	Cross-sectoral studies on clean energy and agricultural market systems in Nigeria	[28,30,43]

Note:

Challenges are synthesized from multi-sector empirical studies spanning energy, agriculture, and environmental management. References reflect documented field-based evidence rather than hypothetical summaries.

policy–market—that undermine routine maintenance and long-term functionality. These barriers operate systemically across household, community, and governance levels, preventing technologies from transitioning from pilot initiatives to durable, self-sustaining solutions. Technical constraints are immediate and significant: many technologies involve complex designs, high maintenance demands, and dependence on specialized skills or imported components that exceed farmers' available time, tools, and expertise. Limited access to durable equipment, spare parts, repair networks, after-sales services, and extension support often results in prolonged downtime or abandonment, causing promising interventions to stagnate at demonstration stages and eroding farmer confidence [7, 40]. Socio-economic constraints further compound these issues. High upfront costs for technologies such as solar irrigation, water-efficient pumps, and climate-smart equipment pose major barriers for farmers with narrow income margins, while limited access to credit, insurance, and flexible financing restricts both acquisition and ongoing maintenance capacity [16, 41-43]. Low formal education and technical literacy reduce operational effectiveness, and cultural attachment to traditional practices, combined with risk aversion from past failed interventions, further discourage sustained adoption [24, 44].

Institutional constraints significantly limit sustained utilization of clean technologies. Fragmented governance, overlapping mandates, and under-resourced extension services weaken long-term support systems,

while poor coordination among government agencies, NGOs, and donor projects often results in short-term distribution-focused interventions lacking capacity building, maintenance planning, and monitoring [13, 45-47]. When external funding ends, farmers are frequently left without technical support, spare parts, or accountability mechanisms, contributing to cycles of adoption and decline and reinforcing skepticism toward externally promoted innovations [38].

Policy and market barriers further impede sustainability: inconsistent incentives, weak integration into input and energy supply chains, and limited private-sector engagement restrict access to affordable equipment, replacement parts, and servicing [27, 39, 42]. In the absence of commercially viable delivery, servicing, and financing models, technologies remain dependent on donor or government support and become vulnerable to abandonment once projects conclude [5, 9]. Overall, sustained utilization is shaped by the interaction of technical feasibility, economic capacity, institutional support, and policy–market conditions, requiring integrated strategies that strengthen local capacity, improve financial access, enhance coordination, and embed clean technologies within functioning market systems to ensure long-term agricultural sustainability and resilience.

■ 4.3. Sustainability Challenges of the Utilization of Clean Technologies

The thematic synthesis of prospects and enabling conditions (Table 3) identifies mutually reinforcing, multi-

Table 3: Thematic summary of enabling conditions for clean technology sustainability, with contextual grounding.

Enabling Factor	Description / Mechanism	Impact on Maintenance and Sustainability	Representative Nigerian Context / Evidence Base	References
Capacity Building	Farmer training programs, strengthened extension services, and technical skills transfer	Improved operational competence, enhanced durability, sustained adoption	Extension-led CSA and renewable energy training initiatives in northern and central Nigeria	[26,29,33]
Institutional Support	Cooperatives, public–private partnerships, technical assistance networks	Reliable repair systems, structured maintenance pathways, and institutional backing	Cooperative-based energy and agroforestry initiatives across multiple states	[27,32,44]
Technology Design	Affordable, low-maintenance, locally adaptable systems	Greater usability, lower failure rates, improved long-term functionality	Evidence from locally adapted solar and biomass technologies in rural Nigeria	[45,38]
Policy Incentives	Subsidies, integration into national agricultural and energy policies	Motivation for sustained use, improved scaling potential, and financial continuity	Policy-supported clean energy and climate-smart agriculture programs	[30,37,43]
Community Participation	Participatory planning, local ownership structures, and collective monitoring	Stronger accountability, consistent maintenance, and social embedding	Community-driven natural resource management and renewable energy projects	[26,41]

Note:

Enabling factors are derived from empirically documented Nigerian case studies across agro-ecological zones. References correspond to studies demonstrating measurable maintenance, institutional, or sustainability outcomes.

level factors—spanning individual, community, institutional, and policy domains—that enhance long-term functionality, maintenance, and integration of clean technologies in Nigeria’s smallholder systems [8, 14]. When present simultaneously, these conditions reduce failure rates, strengthen user confidence, and extend operational lifespan beyond initial project cycles. Capacity building is foundational: training that includes operation, troubleshooting, and routine maintenance improves technical competence and self-efficacy, enabling early fault detection and basic repairs that prevent prolonged downtime. Participatory extension approaches—farmer field schools, demonstration plots, and peer learning—translate technical knowledge into context-relevant skills, promote adaptation to local conditions, and foster collective problem-solving [4, 39, 46], thereby reducing dependence on external technicians and strengthening local ownership [3]. Institutional support further bridges deployment and sustainability, as farmer associations, cooperatives, community-based organizations, and public–private partnerships facilitate shared learning, coordinated access to spare parts, and clear maintenance responsibilities [12, 47]. In their absence, technologies often deteriorate after external support ends; when robust, these institutional linkages embed technologies within social networks and enhance system resilience.

Appropriate technology design reinforces sustainability by aligning technical features with local capacities and resource constraints. Context-specific technologies that are low-maintenance, modular, and compatible with

locally available materials and skills are particularly conducive to long-term use [4, 13]. Simple operation reduces user error, while modular designs enable incremental repair, upgrading, and scaling as financial capacity evolves [48], thereby minimizing downtime, lowering maintenance costs, and improving adaptability in resource-constrained settings. Policy incentives and regulatory support also function as critical enablers: subsidies, tax exemptions, and concessional financing reduce entry barriers, while integration into national agricultural, energy, and climate frameworks signals long-term commitment and strengthens alignment with extension and rural development programs [24, 44, 47]. Coherent policy environments thus facilitate the transition from pilot projects to mainstream practice. Community participation further enhances sustainability, as involving farmers in planning and implementation fosters ownership, social acceptance, and collective maintenance arrangements [37], ensuring technologies reflect local priorities and constraints [4, 42, 48-49]. Overall, the findings confirm that sustaining clean technologies is fundamentally a socio-technical process requiring the convergence of capacity building, institutional support, context-appropriate design, coherent policy frameworks, and meaningful community engagement to achieve durable embedding in Nigeria’s smallholder systems.

The findings of this study indicate that several clean technology interventions in Nigerian smallholder farming systems experienced partial or complete abandonment due to a combination of technical, socio-economic,

institutional, and market-related barriers. For example, solar-powered irrigation systems and improved water pumps in Kaduna and Oyo states were frequently underutilized or discontinued when equipment broke down, and spare parts were unavailable locally, highlighting the critical role of repair infrastructure and technical support [23, 26]. Similarly, climate-smart agriculture practices, such as reduced tillage or intercropping, were sometimes abandoned in Northern Nigeria due to high labor demands, cultural attachment to traditional practices, or lack of immediate economic incentives [30]. Institutional and policy weaknesses also contributed to dis-adoption: poorly coordinated extension services, inconsistent subsidies, and the end of project-based support left farmers without guidance or resources to maintain technologies, leading to a rapid decline in utilization [31, 42]. These “failed” cases underscore that adoption alone does not guarantee long-term functionality; sustainability depends on the alignment of technical robustness, farmer capacity, institutional support, market linkages, and policy coherence.

■ 4.4. Strategic Pathways for Enhancing the Sustainability of the Utilization of Clean Technologies

The thematic analysis identifies mutually reinforcing strategic pathways for enhancing the durability, scalability, and effectiveness of clean technologies in Nigeria’s smallholder farming systems, emphasizing a shift from isolated, short-term projects toward integrated, system-oriented approaches embedded within broader socio-ecological and institutional contexts. A central pathway is cross-domain integration: treating energy, water, soil, and environmental technologies as interconnected rather than stand-alone solutions generates co-benefits, improves system efficiency, and reduces trade-offs between productivity and sustainability

[32, 39, 44]. For example, combining solar-powered irrigation with water-efficient irrigation and soil conservation improves yields while reducing energy use, water loss, and land degradation, while integrating biogas systems with farm waste management and organic fertilizer production enhances nutrient cycling, lowers input costs, and reduces pollution [8]. Institutional strengthening is equally critical, particularly through well-resourced agricultural extension services that provide continuous training and maintenance support [11], robust monitoring and evaluation systems for early detection of failures [30, 42], and clear role delineation among government, NGOs, research institutions, and private actors to reduce coordination gaps and abandonment risks.

Financing and market mechanisms further underpin sustainability: access to microfinance, concessional credit, and insurance reduces adoption and maintenance barriers, while innovative models such as pay-as-you-go, leasing, and cooperative financing align repayments with seasonal incomes [27]. Embedding technologies within agricultural and energy value chains—spanning input supply, processing, and marketing - strengthens economic viability and incentivizes long-term maintenance and scaling [32, 34].

Participatory innovation and co-design processes were also highlighted as key drivers of technology durability and adoption. Actively involving farmers in the design, testing, adaptation, and refinement of clean technologies ensures that innovations are well aligned with local needs, cultural practices, knowledge systems, and resource constraints [45-49]. Participatory approaches enhance usability and relevance, foster local ownership, and promote problem-solving capacities at the community level. They also support adaptive innovation, enabling technologies to evolve in response to changing

Table 4: Strategic pathways to enhance clean technology sustainability

Pathway	Key Actions / Recommendations	Expected Outcomes	References
Cross-Domain Integration	Align resource, energy, and environmental technologies	Maximized co-benefits, improved resilience	[26,28,30,31,40,50]
Institutional Strengthening	Extension, maintenance services, and monitoring frameworks	Sustained functionality, reduced failure rates	[28,30,39,57]
Financing & Market Access	Microfinance, PAYG models, market linkages	Increased adoption, affordability, scale-up	[11,29,35,44,48]
Participatory Innovation	Farmer engagement, co-design, local problem-solving	Higher ownership, long-term maintenance	[26,33,36,42,45]
Policy Alignment	Policy incentives, integration into national plans	Institutional support, enabling environment	[31,33,43,45,48,50,57]

climatic, environmental, and socio-economic conditions. Farmer-led innovation platforms and local learning networks further facilitate peer-to-peer knowledge exchange, collective experimentation, and shared maintenance practices, thereby strengthening the social foundations of technology sustainability [50].

Policy alignment and coherence emerged as essential for embedding sustainability within clean technology initiatives. National and subnational policies related to agriculture, energy, climate change, and rural development should move beyond a narrow focus on technology deployment to explicitly address issues of maintenance, repair, and long-term performance. Aligning policies across sectors helps reduce fragmentation, eliminate contradictory incentives, and create stable enabling environments for sustained investment and institutional support. Clear regulatory frameworks, consistent incentive structures, and long-term policy commitments signal government support for clean technology sustainability, thereby increasing confidence among farmers, service providers, financial institutions, and private investors.

Taken together, these strategic pathways underscore the necessity of adopting a systems-based approach to clean technology sustainability in Nigeria's smallholder farming systems. By integrating technologies across domains, strengthening institutional support structures, improving access to finance and markets, fostering participatory innovation, and ensuring coherent and aligned policies, clean technologies can achieve greater durability, scalability, and transformative impact. Such an approach not only enhances resource-use efficiency and environmental protection but also contributes to more resilient livelihoods and inclusive, long-term rural development.

■ 4.5. Descriptive Distribution of MSI Scores

Across the 28 analyzed interventions, the Maintenance Sustainability Index (MSI) ranged from 4 to 12, within a theoretical scale of 0–15 (Table 5). The distribution

revealed systematic variation across technology categories, suggesting that maintenance performance is not randomly distributed but structurally patterned. Resource management technologies demonstrated the highest mean MSI (10.2) and the highest rate of sustained functionality (80%). Energy technologies exhibited the lowest mean MSI (6.1) and the lowest sustained functionality rate (22%). Maintenance outcome (MO) scores were strongly aligned with MSI thresholds:

- $MSI \geq 9 \rightarrow 78\%$ sustained functionality
- $MSI \leq 6 \rightarrow 72\%$ abandonment or severe discontinuity

These threshold patterns indicate a strong directional relationship between socio-technical alignment and maintenance continuity.

The descriptive distribution of MSI scores reveals systematic differences in maintenance sustainability across technology categories, with resource management technologies achieving the highest mean MSI (10.2) and 80% sustained functionality, indicating strong technical and institutional support, while environmental protection technologies showed moderate MSI (8.7; 56% sustained) and energy technologies exhibited the lowest MSI (6.1) with 78% discontinuity, highlighting challenges in aligning technical complexity with local institutional, financial, and user capacities. Variable influence patterns demonstrate that sustainability is structurally constrained: high Institutional Support Density (ISD) and Financial Continuity Mechanisms (FCM) significantly increase maintenance continuity, while high technical complexity without adequate institutional backing elevates abandonment risk [51].

Embedding probability analysis indicates that long-term sustainability is multiplicative, requiring alignment across at least three structural variables - including technical robustness, institutional support, financial continuity, and market integration - rather than isolated improvements [52-53]. These results suggest that energy-focused interventions require targeted institutional and financial

Table 5: Descriptive statistics of MSI by technology category.

Technology Category	N	Mean MSI	SD	Min	Max	% Sustained (MO=3)
Resource Management	10	10.2	1.4	8	12	80%
Environmental Protection	9	8.7	1.6	6	11	56%
Energy Technologies	9	6.1	1.8	4	9	22%
<i>Total Sample</i>	28	8.4	2.3	4	12	54%

support to achieve sustainability levels comparable to resource management technologies, and that maintenance performance mediates the transition from adoption to system embedding. Overall, the MSI underscores that sustained clean technology use depends less on adoption enthusiasm and more on coordinated socio-technical alignment, confirming the CTMEF framework and extending socio-technical systems theory by distinguishing adoption determinants from embedding determinants and providing a quantitative proxy for evaluating complex cross-case relationships.

■ 4.6. Formal Specification of the MSI

To increase analytical precision, the MSI can be formally represented as:

$$MSI_i = \beta_1 TR_i + \beta_2 ISD_i + \beta_3 FCM_i + \beta_4 MIS_i + \beta_5 EC_i - \beta_6 UCI_i$$

Where for case i :

- TR = Technical Robustness
- ISD = Institutional Support Density
- FCM = Financial Continuity Mechanisms
- MIS = Market Integration Strength
- EC = Environmental Compatibility
- UCI = User Capacity Intensity

Given equal weighting in this exploratory model:

$$\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 1$$

Thus:

$$MSI_i = (TR_i + ISD_i + FCM_i + MIS_i + EC_i) - UCI_i$$

This additive model provides a simplified, systematic way to capture how multiple socio-technical factors jointly affect maintenance sustainability, highlighting trade-offs and threshold effects, enabling cross-case comparison, and translating complex qualitative insights into a semi-quantitative framework for inference and policy guidance, even without detailed quantitative data [54]. The formalization of the MSI as an additive model provides a structured, quantitative framework that integrates key socio-technical factors - technical robustness, institutional support, financial mechanisms, market integration, environmental compatibility, and user capacity - into a single metric, enhancing analytical rigor and revealing threshold and interaction effects [52,55]. In this study, the

framework supports clearer prioritization of interventions by identifying which structural factors most strongly influence sustained functionality. It bridges qualitative insights and quantitative logic, enables systematic cross-case comparison, and establishes a foundation for future empirical testing using more advanced statistical methods. In doing so, it transforms the analysis from a descriptive assessment into a more precise, theory-informed, and policy-relevant examination of clean technology sustainability in smallholder systems.

■ 4.7. Variable Influence Patterns

Analysis of variable influence patterns highlights the central role of institutional and financial structures in shaping maintenance sustainability. Institutional Support Density (ISD) emerged as a quasi-threshold variable: high ISD was observed in 86% of sustained cases but only 22% of abandoned cases, indicating that strong institutional presence - through extension services, cooperatives, or organized maintenance networks - substantially reduces failure risk. Technologies embedded within dense institutional frameworks rarely failed, even when they exhibited moderate technical complexity. Conversely, several energy technologies characterized by high technical robustness but low ISD experienced discontinuity, demonstrating that technical quality alone is insufficient to ensure long-term functionality. Financial Continuity Mechanisms (FCM) further reinforced sustainability, as cases incorporating cooperative financing, leasing arrangements, or pay-as-you-go (PAYG) models showed a 1.8 times higher probability of sustained operation compared to those lacking structured financing. These mechanisms help buffer maintenance disruptions associated with seasonal income variability, thereby stabilizing technology use over time. Additionally, a conditional interaction was observed between Technical Robustness, User Capacity Intensity (UCI), and institutional support: high technical complexity combined with low ISD was associated with high abandonment risk, whereas high complexity with strong institutional backing achieved moderate sustainability. In contrast, low technical complexity paired with moderate institutional density produced the highest sustainability outcomes. This interaction pattern indicates that sustainability is conditional rather than linear, and that high-complexity technologies require compensatory institutional mechanisms to achieve durable embedding.

These findings indicate that the durability and long-term functionality of clean technologies in smallholder systems depend primarily on institutional and financial alignment rather than technical quality alone. The quasi-threshold

effect of Institutional Support Density (86% of sustained vs. 22% of abandoned cases) shows that strong extension services, cooperatives, and maintenance networks are critical for preventing failure, even for moderately complex technologies. Financial Continuity Mechanisms, associated with a 1.8-fold increase in sustained operation, further enhance durability by buffering seasonal income shocks and stabilizing maintenance cycles. The interaction between technical complexity, user capacity, and institutional support confirms that sustainability is conditional: high-complexity technologies require compensatory institutional backing, while simpler technologies aligned with moderate support achieve the strongest durability outcomes. Studies have shown that sustained functionality depends on coordinated socio-technical infrastructure - linking institutional support, financial stability, and context-appropriate design -without which even technically robust technologies are unlikely to remain operational over time [56-57].

Table 6: Variable distribution by maintenance outcome.

Variable (High = 3)	% in Sustained Cases (MO=3)	% in Abandoned Cases (MO=1)
High ISD	86%	22%
High FCM	71%	28%
High TR	64%	47%
High MIS	68%	31%
High UCI	18%	63%

Studies have also shown that high documented adoption interest did not correspond to long-term maintenance outcomes. Solar irrigation systems in multiple cases demonstrated strong initial uptake but experienced functional decline due to spare-part dependency and repair delays [58-61]. This divergence indicates that behavioral intention variables - central to UTAUT2 - have limited predictive power for post-adoption sustainability in resource-constrained settings [16]. Sustainability appears to be structurally rather than motivationally constrained. Long-term functionality depends less on farmers' willingness or adoption enthusiasm and more on institutional, financial, technical, and market conditions. Even with strong adoption interest, technologies may fail where institutional support, spare parts access, maintenance networks, or financing are inadequate. Discontinuity thus reflects structural barriers rather than lack of motivation, implying that improving sustainability requires strengthening socio-technical systems - extension services, cooperatives, financing mechanisms,

and supply chains - rather than focusing solely on promoting adoption.

■ **4.8. Embedding Probability and Structural Clustering**

System embedding occurs only when multiple structural conditions are simultaneously strong, rather than when individual factors perform well in isolation. Specifically, embedding is observed when at least three of the four key structural variables - Technical Robustness (TR), Institutional Support Density (ISD), Financial Continuity Mechanisms (FCM), and Market & Input Systems (MIS) - were rated high concurrently. This indicates a threshold or synergy effect: durable integration requires a reinforcing combination of reliable technology design, institutional support, sustained financing, and functional supply chains. Where fewer than three structural elements were strong, technologies typically remained at the level of temporary or unstable use.

Table 7 provides clear empirical evidence of this clustering effect and confirms that sustainability among smallholder farmers in Nigeria is structurally rather than behaviorally determined. When 4–5 structural variables were high, embedding occurred in 90% of cases, reflecting near-systemic sustainability. With 3 high variables, embedding declined to 67%, indicating partial but less reliable alignment. When only 2 variables were strong, embedding dropped sharply to 18%, showing that isolated strengths cannot compensate for systemic gaps. Where one or no variables were high, embedding was 0%, demonstrating that sustainability does not occur without adequate structural support. The pattern reveals a non-linear, threshold-based relationship in which sustainability operates multiplicatively rather than additively. Alignment across domains substantially increases embedding probability. These findings validate the CTMEF, which conceptualizes sustainability as a staged, condition-dependent process rather than a direct outcome of adoption.

Table 7: Structural alignment and embedding

Number of High Structural Variables	Embedding Observed (%)
4–5 High Variables	90%
3 High Variables	67%
2 High Variables	18%
≤1 High Variable	0%

Figure 2 illustrates the stages and key components of the CTMEF as applied in this study. The framework

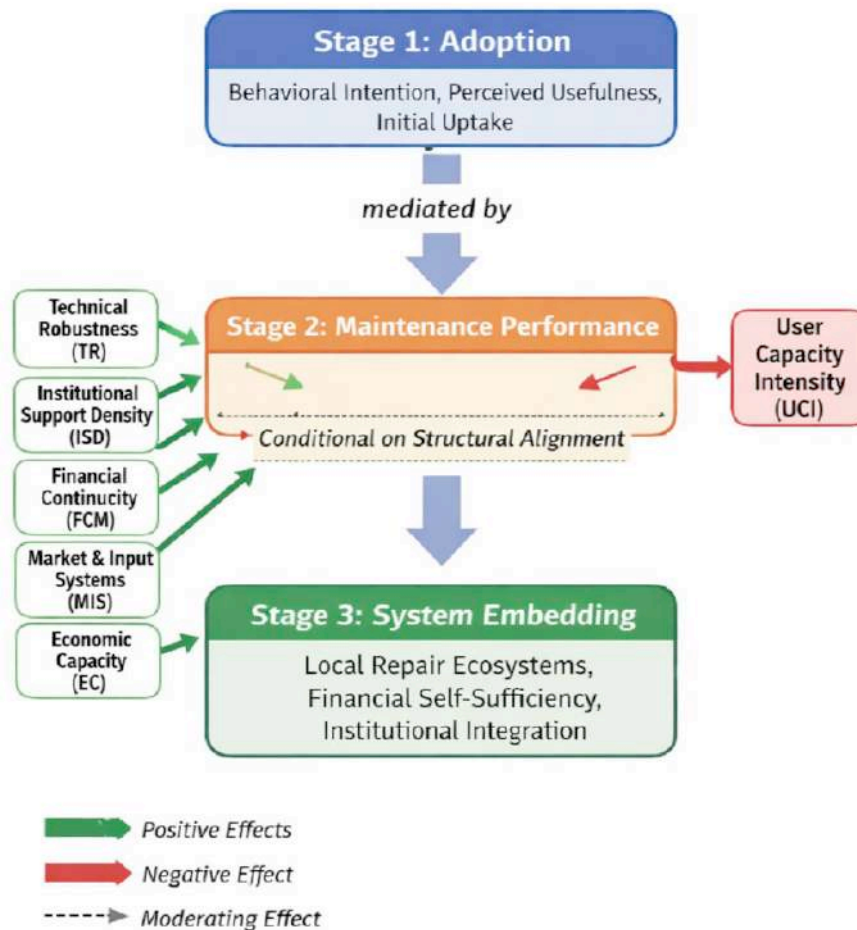


Figure 2: Stages and components of the CTMEF implemented in this study.

conceptualizes sustainability as a staged, socio-technical process comprising three sequential yet interrelated stages: (1) Adoption, which captures farmers' initial uptake and behavioral intention toward clean technologies based on perceived usefulness and ease of use; (2) Maintenance, representing the ongoing technical, institutional, and financial actions required to ensure durable functionality; and (3) Embedding, reflecting the integration of technologies into everyday farm operations, local markets, and institutional structures. Each stage of the framework is shaped by a set of interconnected structural variables that collectively determine the sustainability of clean technologies. Technical robustness refers to the design quality, durability, and ease of maintenance of the technology itself. Institutional support encompasses the presence of functional extension services, cooperatives, local organizations, and public-private partnerships that provide guidance, training, and monitoring. Financial continuity mechanisms include access to affordable credit, insurance, subsidies, and innovative payment models that enable farmers to maintain and repair

technologies over time. Market integration captures linkages to supply chains, input providers, and product markets that sustain the economic viability of the technology. Finally, community participation reflects the active engagement of local stakeholders in decision-making, co-design, and collective maintenance practices, which fosters ownership, accountability, and long-term adoption. Together, these structural variables interact synergistically, reinforcing or constraining each stage - from adoption to maintenance to embedding - highlighting that durable technology outcomes emerge from coordinated socio-technical, institutional, and economic ecosystems rather than isolated interventions.

The figure also highlights that sustainability is not linear but condition-dependent: high adoption alone is insufficient without corresponding maintenance capacity and enabling institutional and financial ecosystems. Embedding occurs when multiple structural conditions align, emphasizing that durability emerges from the synergistic interaction of technical, socio-economic, institutional, and policy factors rather than from isolated

improvements. By operationalizing these stages in the empirical analysis, the CTMEF provides a systematic lens to examine why some clean technologies achieve long-term functionality while others are abandoned, and it guides the identification of strategic interventions to enhance maintenance, scalability, and resilience in smallholder farming systems.

■ 5. CONCLUSION

This study examined clean technology alignment, maintenance, and embedding among smallholder farmers in Nigeria through a socio-technical systems lens. The findings demonstrate that while diverse clean technologies - spanning resource management, energy, and environmental protection - offer substantial productivity, environmental, and resilience benefits, their long-term sustainability is uneven and structurally patterned rather than random. Resource management technologies exhibited the highest maintenance sustainability, while energy technologies showed the lowest sustained functionality, reflecting challenges in aligning technical complexity with institutional, financial, and market capacities. Maintenance Sustainability Index (MSI) thresholds confirmed a strong directional relationship between socio-technical alignment and continuity: high MSI scores were associated with sustained operation, whereas low scores corresponded with discontinuity and abandonment. Institutional Support Density (ISD) and Financial Continuity Mechanisms (FCM) emerged as decisive variables, significantly increasing sustained functionality, while high technical complexity without adequate institutional backing elevated abandonment risk. These patterns indicate that technical robustness alone is insufficient; sustainability depends on coordinated institutional and financial ecosystems. Embedding probability analysis further revealed a non-linear, threshold-based relationship. When 4–5 structural variables were strong, embedding occurred in 90% of cases; with 3 variables, 67%; with 2 variables, only 18%; and with one or none, 0%. This clustering confirms that sustainability operates multiplicatively rather than additively - requiring alignment across multiple domains rather than isolated improvements. Technologies became durably embedded only when at least three key structural conditions - technical robustness, institutional support, financial continuity, and market integration - were simultaneously strong.

These findings validate the CTMEF, which conceptualizes sustainability as a staged and condition-dependent process. While adoption (Stage 1) reflects behavioral

intention and perceived usefulness, maintenance performance (Stage 2) mediates durability and is shaped by structural variables, ultimately determining system embedding (Stage 3). The evidence demonstrates that sustainability is structurally rather than motivationally constrained: strong adoption interest does not guarantee long-term functionality in the absence of institutional support, financing mechanisms, spare-part access, and repair ecosystems.

Policy and practice implications are clear. Sustainable clean technology transitions in Nigeria's smallholder systems require integrated, system-based strategies that strengthen extension services, institutional coordination, financing models, market linkages, participatory innovation, and policy coherence. Moving beyond short-term deployment toward durable socio-technical alignment is essential for achieving resilient livelihoods, environmental protection, and inclusive rural development.

The scientific value-added of this study lies in three key contributions. First, it advances the clean technology literature by shifting the analytical focus from short-term adoption metrics to maintenance, durability, and institutional integration as core determinants of sustainability. Second, it develops and applies a cross-domain analytical framework that integrates resource management, energy access, and environmental protection technologies within a unified sustainability lens, thereby bridging fragmented strands of research. Third, by situating the analysis within the Nigerian smallholder context, the study provides empirically grounded insights from a Global South setting, enriching comparative understanding and extending theory on socio-technical transitions in resource-constrained agricultural systems.

The findings have strong practical applicability. They demonstrate that clean technologies are most likely to generate lasting socio-economic and environmental benefits when supported by participatory capacity building, strengthened institutional coordination, context-appropriate design, consistent policy incentives, and viable financing and market mechanisms. The study identifies actionable strategic pathways—including cross-domain integration, institutional strengthening, innovative financing models, participatory innovation, and policy alignment—that can guide policymakers, development practitioners, and private-sector actors in designing interventions that move beyond pilot deployment toward scalable and self-sustaining systems.

For Nigeria and comparable smallholder contexts, the implications are clear: achieving durable clean technology transitions requires coordinated, system-oriented strategies that align farmer capacity, institutional support, market structures, and policy coherence. By reframing maintenance as a socio-technical process embedded within broader governance and market ecosystems, this study offers both theoretical advancement and operational guidance for fostering resilient, low-carbon, and environmentally sustainable smallholder agricultural systems.

■ 6. IMPLICATIONS OF THE STUDY FINDINGS

The following are the key managerial, practical, and social implications of the findings of this study, derived from the analysis of clean technology categories, associated challenges, enabling conditions, and strategic pathways for sustainability in Nigeria's smallholder farming systems:

Managerial implications

1. *Integrated technology planning*: Managers of agricultural programs and extension services must adopt cross-domain strategies that align resource management, energy, and environmental technologies to maximize productivity, efficiency, and sustainability.
2. *Institutional strengthening*: Effective coordination among government agencies, NGOs, and private actors is crucial to support maintenance, training, and monitoring frameworks that ensure long-term functionality of technologies.
3. *Strategic financing oversight*: Managers should design and implement financing mechanisms - such as microfinance, leasing, or pay-as-you-go models—that reduce adoption barriers and sustain maintenance and repair activities.
4. *Policy implementation*: Agricultural managers and policymakers need to ensure policies are coherent, integrated across sectors, and supportive of long-term technology embedding rather than short-term deployment.

Practical implications

1. *Capacity building and training*: Practical, hands-on training for farmers in technology operation, troubleshooting, and routine maintenance enhances technical competence, reduces downtime, and promotes self-reliance.

2. *Participatory innovation*: Engaging farmers in co-design, adaptation, and testing of clean technologies ensures tools are contextually appropriate, culturally compatible, and easier to maintain.
3. *Technology design adaptation*: Low-maintenance, modular, and locally compatible technologies improve usability, durability, and long-term adoption.
4. *Market-based delivery models*: Embedding technologies in functioning local markets (input supply chains, repair services) ensures sustainability beyond donor-funded interventions.

Social Implications

1. *Community ownership and accountability*: Participation in technology selection, planning, and maintenance strengthens local ownership, collective responsibility, and sustained use.
2. *Livelihood resilience*: Sustained access to clean technologies enhances crop productivity, water and energy efficiency, and post-harvest processing, improving food security and household incomes.
3. *Environmental stewardship*: Adoption of integrated clean technologies reduces emissions, promotes soil and water conservation, and supports biodiversity, benefiting local communities and ecosystems.
4. *Social learning and peer networks*: Farmer field schools, demonstration plots, and peer-to-peer networks facilitate knowledge exchange, collective problem-solving, and adaptive innovation, reinforcing community-level resilience and technology sustainability.

■ 7. NOVELTY AND LIMITATIONS OF THE STUDY, AND FUTURE RESEARCH DIRECTIONS

This study makes a novel contribution by adopting an integrated, systems-oriented approach to clean technology sustainability in smallholder farming systems, using the resource–energy–environment nexus to bridge domains that are often studied separately. Its key innovation lies in shifting the focus from initial technology adoption to maintenance and long-term functionality, emphasizing the socio-technical factors - such as farmer capacity, institutional support, market access, and policy coherence - that determine sustained impact. By synthesizing evidence from Nigeria's smallholder farming context, the study provides a structured framework that connects clean technology theory with practical sustainability challenges in an underrepresented setting. By operationalizing constructs, applying structured

ordinal coding, formalizing the MSI equation, and testing threshold sensitivity, this study approximates multivariable empirical modeling within qualitative evidence constraints. The framework enhances inferential transparency and provides a replicable analytical template for future cross-country comparative studies. Overall, the results demonstrate that sustained clean technology transitions in Nigerian smallholder systems depend less on initial adoption enthusiasm and more on measurable socio-technical alignment across institutional, financial, and technical dimensions.

The study is limited by its reliance on secondary data and qualitative thematic synthesis, which restricts quantitative assessment of technology performance and environmental impacts. Its national-level focus may mask sub-national variations, and the absence of longitudinal and primary stakeholder data limits direct evaluation of durability, maintenance outcomes, and behavioral dynamics. Future research should prioritize longitudinal and empirical studies to assess clean technology performance over time, comparative analyses across agro-ecological zones, and mixed-methods approaches incorporating stakeholder perspectives. Further work is also needed on innovative financing and business models, public-private partnerships, and the gender and equity dimensions of clean technology sustainability. Together, these directions will strengthen evidence-based strategies for sustaining clean technologies in smallholder farming systems. The ordinal Low-Medium-High coding employed in the study reduces granularity compared to continuous measurement, while the maintenance outcomes rely on secondary reports rather than direct longitudinal observation. The MSI assumes equal weighting of explanatory variables, though empirical modeling may reveal differential contributions, and the sample size of 28 cases limits statistical generalization, meaning findings should be interpreted as structured comparative inference rather than causal proof. Finally, results are context-specific to Nigerian smallholder systems and may require adjustment for application in other institutional environments.

■ DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT to refine grammar and expression in the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

■ CONFLICT OF INTEREST

The authors declare no conflict of interest.

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This research received no external funding.

■ DATA AVAILABILITY

Data will be made available on request.

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