IRGS Journal of Science, Engineering and Technology
Website: www.irgspublisher.com
Email: office@irgspublisher.com
Vol-1, Iss-1, May–June 2026
ISSN: XXXX-XXXX

Science, Technology and Innovation for Capacity Building Toward Sustainable Futures: Bridging Global Challenges and Local Realities

Usman Rufai Fakai[1], Bashiru Muhammad Suru[2], Zeenat Abdullahi[3], Aliyu Jabbo Bunza[4], Junaidu Yusuf[5], Muhammad Abdullahi Argungu[6]

[1]Department of Chemistry Education, Adamu Augie College of Education, P.M.B. 1012, Argungu, Kebbi State, Nigeria.
[2]Department of Chemistry, Adamu Augie College of Education, Argungu, Kebbi State, Nigeria.
[3]Department of Chemistry, Adamu Augie College of Education, Argungu, Kebbi State, Nigeria.
[4]Department of Chemistry, Adamu Augie College of Education, Argungu, Kebbi State, Nigeria.
[5]Technical Education Department, Federal College of Education, Gidan Madi, Sokoto State, Nigeria.
[6]Department of Chemistry, Adamu Augie College of Education, Argungu, Kebbi State, Nigeria.

Article History:
Received: 13/05/2026
Accepted: 08/06/2026
Published: 22/06/2026

Corresponding Author:
Usman Rufai Fakai

Abstract

This paper proposes and applies a Science, Technology, and Innovation (STI) capacity framework for advancing sustainable futures by connecting global sustainability challenges with local implementation realities. Drawing on innovation systems and capacity development theory, the framework positions STI as a driver of human, institutional, technological, and collaborative capacities that enable effective sustainability action. Using a mixed-methods approach that combines survey evidence and stakeholder perspectives, the study analyzes links between STI inputs, capacity formation, localization processes, and sustainability outcomes. Findings indicate that STI investments significantly strengthen capacity, while capacity factors mediate the relationship between innovation and measurable sustainability performance. Institutional support, skills development, and multi-actor partnerships emerge as critical enablers of successful technology adoption. The results align with global sustainability assessments emphasizing innovation and capacity building as key implementation mechanisms, highlighting integrated capacity systems as essential for durable local impact.

Keywords: Science and Technology Innovation (STI); Capacity Building; Sustainable Development; Innovation Systems.

Article Citation: Usman Rufai Fakai, Bashiru Muhammad Suru, Zeenat Abdullahi, Aliyu Jabbo Bunza, Junaidu Yusuf & Muhammad Abdullahi Argungu (2026). Science, Technology and Innovation for Capacity Building Toward Sustainable Futures: Bridging Global Challenges and Local Realities. **IRGS Journal of Science, Engineering and Technology (IRGSJSET),** Vol-1(Iss-1), 19–28.

Introduction

Sustainable development has emerged as one of the defining global priorities of the twenty-first century, driven by escalating climate change, environmental degradation, energy insecurity, and widening socio-economic inequalities. These interconnected challenges are global in scale but uneven in impact, often placing disproportionate pressure on developing regions with limited technical and institutional capacity. Addressing such complex problems requires more than policy intent; it demands robust capacity built through science, technology, and innovation (STI). Increasingly, international sustainability frameworks recognize STI not merely as supportive tools but as central mechanisms for enabling practical, scalable, and context-responsive solutions. The United Nations 2030 Agenda for Sustainable Development explicitly identifies science, technology, innovation, and capacity building as key means of implementation across the Sustainable Development Goals (SDGs) (United Nations, 2015).

The concept of building capacities for sustainable futures emphasizes the development of human skills, institutional strength, technological infrastructure, and collaborative networks necessary to translate sustainability goals into measurable outcomes. Capacity building extends beyond training to include research systems, innovation ecosystems, and adaptive implementation structures that allow societies to respond effectively to evolving environmental and developmental pressures. In this context, STI functions as both a driver and an enabler: scientific research generates reliable knowledge about environmental systems and risks; technology transforms knowledge into applicable tools and processes; and innovation systems support diffusion, adaptation, and continuous improvement. This integrated role positions STI as a critical bridge between global sustainability challenges and local realities.

Contemporary climate and sustainability assessments consistently underscore the decisive role of technology and innovation in mitigation and adaptation pathways. The Intergovernmental Panel on Climate Change (IPCC) concludes that deep reductions in greenhouse gas emissions and effective climate resilience strategies depend heavily on advances in energy technologies, efficiency systems, digital monitoring, and low-carbon infrastructure (IPCC, 2022). Renewable energy systems, smart grids, environmental sensing technologies, advanced materials for pollution control, and data-driven decision tools are among the innovations reshaping sustainability practice. However, the effectiveness of these technologies depends not only on their existence but on the capacity of institutions and communities to adopt, manage, and adapt them within local contexts.

Innovation systems theory provides a useful lens for understanding how technological capability translates into development outcomes. Foundational work by Freeman (1987) and Lundvall (1992) emphasizes that innovation is not an isolated event but a systemic process involving interactions among universities, industry, government, and users. These innovation ecosystems determine how knowledge is produced, shared, and applied. Regions with stronger research institutions, supportive policies, and active collaboration networks tend to demonstrate higher adaptive capacity and more effective technology uptake. From this perspective, building sustainability capacity requires strengthening the structures that support learning, experimentation, and knowledge transfer — not simply importing technologies.

At the same time, sustainability challenges are inherently local in their manifestation. Climate impacts, pollution burdens, energy access gaps, and resource constraints vary across ecological and socio-economic settings. Solutions must therefore be localized through processes of adaptation, co-creation, and community engagement. Research on commons governance and local institutional adaptation shows that context-sensitive approaches outperform uniform, top-down interventions in managing environmental resources (Ostrom, 1990). Bridging global challenges with local realities thus requires combining globally informed scientific and technological advances with locally grounded implementation strategies. Capacity building becomes the mediating pathway through which STI is translated into locally effective action.

Education and skills development further reinforce this linkage. Knowledge and technical competence are repeatedly identified as prerequisites for sustainability transitions. UNESCO's Education for Sustainable Development framework stresses that scientific literacy, technical skills, and problem-solving competencies are essential for enabling individuals and institutions to participate meaningfully in sustainability efforts (UNESCO, 2017). Without adequate human capacity, even well-designed technologies remain underutilized or unsustainable in practice. Therefore, STI-driven capacity building must include workforce development, professional training, and interdisciplinary learning.

Despite broad agreement on the importance of STI for sustainability, gaps remain in understanding how science, technology, and innovation concretely build capacity that leads to sustainable outcomes — particularly in contexts where institutional and technical resources are constrained. Many studies examine individual technologies or policies, but fewer integrate STI inputs, capacity mechanisms, localization processes, and sustainability outcomes within a single analytical framework. There is a need for structured models that explain how STI investments and innovation ecosystems translate into measurable sustainability gains through multi-level capacity development.

This paper addresses that need by developing and applying a conceptual and analytical framework that links science, technology, and innovation systems to capacity building mechanisms and sustainable futures outcomes. The framework positions STI as the driver layer, capacity building as the mediating layer, and sustainability performance as the outcome layer, while emphasizing localization and adoption processes as the bridge between global solutions and local realities. Grounded in innovation systems theory, sustainability transition research, and international development frameworks, the study aims to clarify pathways through which STI contributes to practical sustainability progress.

By articulating these relationships, the paper contributes to ongoing scholarly and policy discussions on how to operationalize the theme of building capacities for sustainable futures. It provides a structured basis for empirical investigation, policy design, and program evaluation in areas such as renewable energy adoption, environmental management, and green technology deployment. Ultimately, strengthening STI-driven capacity offers one of the most credible routes for transforming sustainability commitments into durable, locally relevant outcomes.

Literature Review

Science, Technology, Innovation, and Capacity Building for Sustainable Futures

The relationship between science, technology, and innovation (STI) and sustainable development has been widely examined across sustainability science, innovation studies, and development policy literature. A consistent theme across these bodies of work is that technological progress alone does not guarantee sustainability outcomes; rather, outcomes depend on how effectively societies build the capacities required to generate, adapt, govern, and diffuse innovations. This section reviews major theoretical and empirical contributions that link STI systems with capacity building and sustainability transitions.

Science, Technology, and Innovation as Drivers of Sustainable Development

Global sustainability frameworks consistently position STI as a central enabler of sustainable development pathways. The United Nations 2030 Agenda identifies science, technology, and innovation as core "means of implementation" across multiple Sustainable Development Goals, particularly in energy, industry, climate action, and environmental protection (United Nations, 2015). STI contributes by expanding solution spaces — enabling renewable energy systems, pollution control technologies, resource efficiency tools, and environmental monitoring capabilities.

Climate mitigation and adaptation research strongly reinforces this position. The IPCC's Sixth Assessment Report concludes that achieving deep decarbonization requires rapid innovation and deployment across energy supply, storage, transport, buildings, and industrial systems, supported by enabling policies and institutional capacity (IPCC, 2022). Technology cost reductions — such as those observed in solar photovoltaics and wind power — have been linked directly to sustained innovation, learning-by-doing, and research investment. Grubler, Wilson, and Nemet (2016) show that energy transitions historically follow patterns driven by cumulative innovation, infrastructure development, and diffusion dynamics rather than single breakthrough inventions.

However, sustainability scholars caution against purely techno-centric approaches. Technology must be embedded in social, institutional, and governance contexts to produce durable sustainability benefits. This broader view has given rise to sustainability transitions research, which studies how technological, social, and institutional changes co-evolve to enable system-wide transformation (Geels, 2002; Markard, Raven, & Truffer, 2012).

Innovation Systems and Capacity Formation

Innovation systems theory provides a foundational framework for understanding how STI contributes to capacity building. Freeman (1987) first articulated the concept of national innovation systems as networks of institutions in the public and private sectors whose activities and interactions initiate, import, modify, and diffuse new technologies. Lundvall (1992) further emphasized interactive learning and knowledge exchange among firms, universities, and governments as central mechanisms of innovation capacity.

Within this perspective, capacity is not limited to technical skill but includes institutional arrangements, research infrastructure, financing systems, and collaborative networks that support continuous learning and problem-solving. Edquist (1997) argues that innovation systems function effectively when they support knowledge creation, competence building, and technology diffusion simultaneously. Regions that invest in research institutions, technical education, and industry–academia collaboration tend to demonstrate higher adaptive and innovative capacity.

Empirical studies support this systemic view. Fagerberg, Srholec, and Verspagen (2010) found that differences in innovation system strength explain significant variation in development performance across countries. Strong systems — characterized by higher R&D intensity, education levels, and institutional quality — are more effective at translating technological opportunities into socio-economic gains. This suggests that STI contributes to sustainable futures primarily when it is accompanied by deliberate capacity-building structures.

Capacity Building and Sustainable Development Practice

Capacity building is widely recognized in development literature as a multidimensional process involving human, institutional, and organizational strengthening. The United Nations Development Programme defines capacity development as the process through which individuals, organizations, and societies obtain, strengthen, and maintain the capabilities to set and achieve development objectives over time (UNDP, 2009). In sustainability contexts, this includes scientific literacy, technical competencies, regulatory capability, and organizational effectiveness.

Education plays a particularly important role in sustainability capacity. UNESCO's Education for Sustainable Development framework argues that scientific and technical knowledge, systems thinking, and problem-solving skills are essential for enabling sustainability action across sectors (UNESCO, 2017). Without adequate human capital, technology transfer efforts frequently fail or produce limited impact. Cohen and Levinthal (1990) describe this as absorptive capacity — the ability of organizations to recognize, assimilate, and apply new knowledge — which depends strongly on prior related knowledge and skills.

At the institutional level, governance quality and policy coherence influence whether STI investments translate into sustainable outcomes. Ostrom (1990) demonstrates that locally adapted institutional arrangements significantly improve environmental resource management outcomes compared to uniform centralized models. This finding supports the argument that capacity building must include institutional learning and context-sensitive governance, not only technology provision.

Technology Diffusion, Localization, and Adoption

Technology diffusion research highlights that adoption is shaped by social, economic, and institutional conditions. Rogers' (2003) diffusion of innovations theory explains how new technologies spread through social systems over time, influenced by perceived advantage, compatibility, complexity, trialability, and observability. In sustainability fields such as renewable energy and environmental technology, adoption rates vary widely depending on financing access, technical support, regulatory frameworks, and user capabilities.

Sustainability transitions scholars emphasize niche experimentation and local learning processes as critical for scaling innovations. Geels (2002) proposes the multi-level perspective, where innovations emerge in protected niches, interact with existing regimes, and respond to broader landscape pressures. Markard, Raven, and Truffer (2012) show that successful sustainability transitions typically involve long-term interaction between technological innovation, policy support, and user practices. These findings reinforce the role of localized capacity building and pilot implementation in bridging global solutions with local realities.

Synthesis and Research Gap

Across the literature, there is strong agreement that STI is indispensable for sustainable development and that capacity building is the mechanism through which STI produces lasting impact. Innovation systems theory explains how knowledge and technology are generated and diffused; capacity development theory explains how actors become able to use and sustain them; and sustainability transitions research explains how system-level change occurs. Major global assessments, including the IPCC and UN SDG framework, integrate these insights by identifying technology and capacity as co-requirements for sustainability progress (IPCC, 2022; United Nations, 2015).

Nevertheless, existing studies often treat technology, capacity, and sustainability outcomes as partially separate domains. There remains a need for integrated analytical frameworks that explicitly connect STI inputs, multi-level capacity building mechanisms, localization processes, and measurable sustainability outcomes within a single model. This paper builds on the reviewed literature to advance such an integrated framework and apply it to empirical sustainability problem contexts.

Theoretical and Conceptual Framework

This study is grounded in an integrated theoretical framework that connects innovation systems theory, capacity development theory, and sustainability transitions theory to explain how science, technology, and innovation (STI) contribute to building capacities for sustainable futures. The framework assumes that sustainable outcomes do not arise from technology alone but from the interaction between technological inputs, institutional structures, human competencies, and localized adoption processes. By combining these theoretical strands, the paper explains how global sustainability challenges can be addressed through locally embedded capacity-building pathways.

Innovation Systems Theory

Innovation systems theory provides the primary foundation for understanding how scientific and technological knowledge is generated, diffused, and utilized within an economy or sector. Early formulations by Freeman (1987) defined innovation systems as networks of institutions whose interactions determine the innovative performance of firms and nations. Lundvall (1992) expanded this view by emphasizing interactive learning and user–producer relationships, arguing that innovation is fundamentally a social and institutional process rather than a purely technical one.

From this perspective, capacity building is embedded within innovation systems through research institutions, universities, firms, policy agencies, and intermediary organizations. These actors collectively shape knowledge production, skills formation, and technology diffusion. Edquist (1997) notes that well-functioning innovation systems perform key functions including competence building, knowledge development, and market formation. Empirical analyses show that countries with stronger innovation systems — reflected in R&D investment, higher education quality, and institutional effectiveness — achieve more robust technological and developmental outcomes (Fagerberg, Srholec, & Verspagen, 2010).

For sustainability challenges, the innovation systems lens implies that clean technologies, environmental monitoring tools, and renewable energy solutions scale effectively only where systemic learning and institutional support exist. Thus, STI-driven sustainability requires strengthening the structures that enable continuous innovation and adaptation, not only introducing new technologies.

Capacity Development Theory

Capacity development theory complements innovation systems theory by focusing on the abilities of individuals, organizations, and institutions to perform functions effectively, efficiently, and sustainably. Development scholarship increasingly treats capacity not as a one-time output but as a long-term process of capability enhancement. The United Nations Development Programme conceptualizes capacity development as the process through which actors acquire and maintain capabilities to achieve their own development objectives (UNDP, 2009).

At the organizational level, the concept of absorptive capacity is especially relevant. Cohen and Levinthal (1990) define absorptive capacity as the ability to recognize the value of new external knowledge, assimilate it, and apply it commercially or operationally. Absorptive capacity depends on prior knowledge, technical skills, and learning structures — all central elements of STI-based capacity building. Zahra and George (2002) further develop this concept by distinguishing between potential absorptive capacity (knowledge acquisition and assimilation) and realized absorptive capacity (transformation and exploitation).

In sustainability contexts, capacity development includes technical training, scientific literacy, regulatory competence, and organizational learning. UNESCO links education and technical competence directly to sustainable development outcomes, arguing that sustainability transitions depend on problem-solving skills, interdisciplinary knowledge, and innovation capability (UNESCO, 2017). These perspectives support the view that STI contributes to sustainable futures primarily when accompanied by deliberate investments in human and institutional capacity.

Sustainability Transitions Theory

Sustainability transitions theory explains how large socio-technical systems — such as energy, transport, and environmental management — undergo long-term transformation. This body of work rejects linear models of technological change and instead emphasizes co-evolution among technology, policy, markets, user practices, and cultural meanings. A central model in this field is the multi-level perspective proposed by Geels (2002), which conceptualizes transitions as interactions among niche innovations, dominant regimes, and broader landscape pressures.

Within this framework, new sustainable technologies often emerge in protected niches where experimentation and learning occur. Over time, with sufficient support and alignment with policy and market conditions, these innovations can challenge and transform existing regimes. Markard, Raven, and Truffer (2012) show that sustainability transitions typically require long-term policy support, stakeholder networks, and institutional change alongside technological advancement. This reinforces the argument that building sustainability capacity requires coordinated development of technological and institutional capabilities.

Climate and energy transition assessments adopt similar systemic views. The IPCC emphasizes that mitigation and adaptation pathways depend on enabling conditions including finance, governance, institutional capacity, and innovation systems — not technology alone (IPCC, 2022). Technology deployment success varies widely across regions due to differences in these enabling capacities.

Integrated Conceptual Model for the Study

Drawing from these theoretical traditions, this study adopts an integrated conceptual model in which:

1. Science, Technology, and Innovation inputs (research outputs, green technologies, digital tools, R&D systems) function as primary drivers;
2. Capacity building mechanisms (human skills, institutional strength, technological infrastructure, collaborative networks) act as mediators;
3. Localization and adoption processes (adaptation, pilot implementation, user engagement) serve as translation pathways;
4. Sustainable futures outcomes (clean energy uptake, pollution reduction, resource efficiency, resilience) represent measurable results.

This integrated structure reflects the innovation systems emphasis on institutionalized learning (Lundvall, 1992; Freeman, 1987), the capacity development focus on capabilities and absorptive capacity (Cohen & Levinthal, 1990; UNDP, 2009), and the sustainability transitions focus on socio-technical transformation (Geels, 2002; Markard et al., 2012). It also aligns with global sustainability policy frameworks that identify STI and capacity building as joint pillars of implementation (United Nations, 2015; IPCC, 2022).

The framework therefore provides an analytical basis for examining how STI initiatives translate into sustainability outcomes through multi-level capacity formation and context-sensitive adoption processes. Subsequent sections operationalize this framework into measurable variables and empirical procedures.

Methodology

This chapter describes the research design, data sources, measurement framework, and analytical procedures used to examine how science, technology, and innovation (STI) contribute to capacity building for sustainable futures. The methodological choices are guided by established social science and sustainability research approaches and are aligned with the integrated theoretical framework combining innovation systems, capacity development, and sustainability transitions perspectives (Freeman, 1987; Lundvall, 1992; Geels, 2002).

Research Design

The study adopts a mixed-methods design, combining quantitative and qualitative approaches to capture both measurable capacity indicators and contextual implementation processes. Mixed-methods designs are widely recommended when investigating complex socio-technical systems because they allow triangulation between statistical patterns and institutional or behavioral explanations (Creswell & Plano Clark, 2018). Sustainability and innovation studies frequently employ mixed designs to link technology adoption metrics with governance and organizational factors (Markard, Raven, & Truffer, 2012).

A convergent parallel strategy is applied, in which quantitative and qualitative data are collected within the same study phase, analyzed separately, and then integrated at the interpretation stage. This design improves validity by comparing results across methods (Creswell, 2014).

Study Scope and Unit of Analysis

The unit of analysis is the STI-enabled sustainability initiative or institution (e.g., research centers, technology projects, renewable energy programs, environmental monitoring initiatives, or innovation hubs). This aligns with innovation systems research, which treats organizations and networks as primary loci of innovation capacity (Edquist, 1997; Fagerberg, Srholec, & Verspagen, 2010).

The study scope includes initiatives that demonstrate at least one of the following:

1. Application of scientific or technological solutions to sustainability problems
2. Structured capacity-building components (training, partnerships, infrastructure)
3. Local adaptation or deployment of green or environmental technologies

Sampling Strategy

A purposive sampling technique is used to select cases and respondents with direct involvement in STI and sustainability initiatives. Purposive sampling is appropriate in innovation and policy research where specialized knowledge is required from participants (Yin, 2018).

Participant categories include:

1. Researchers and technical experts
2. Project managers and innovation hub coordinators
3. Policy or regulatory officials
4. Technology users or implementers
5. Institutional administrators

Qualitative case selection follows information-rich case logic, recommended for exploratory and explanatory case studies (Patton, 2015).

Data Collection Methods

Quantitative Data

Quantitative data are collected using a structured questionnaire designed to measure STI inputs, capacity dimensions, and sustainability outcomes. Survey-based measurement is widely used in innovation capacity and absorptive capacity research (Cohen & Levinthal, 1990; Zahra & George, 2002).

The questionnaire includes Likert-scale and index-based items covering:

1. R&D activity and technology availability
2. Technical skills and training exposure
3. Institutional support structures
4. Collaboration intensity
5. Technology adoption levels
6. Sustainability performance indicators

Where available, secondary indicators are incorporated, such as:

1. Energy use profiles
2. Technology deployment counts
3. Environmental performance metrics

Use of multiple indicators strengthens construct validity (Creswell, 2014).

Qualitative Data

Qualitative data are obtained through semi-structured interviews and document analysis. Semi-structured interviews allow exploration of institutional learning, technology adaptation, and governance processes while maintaining comparability across respondents (Kvale & Brinkmann, 2009).

Document sources include:

1. Project reports
2. policy documents
3. institutional STI strategies
4. sustainability plans

Document analysis is recommended in governance and innovation research to capture formal capacity structures (Bowen, 2009).

Measurement of Key Constructs

Construct measurement follows established theory-based operationalization principles (DeVellis, 2017).

STI Inputs are measured through indicators such as R&D intensity, technology availability, and innovation infrastructure — consistent with innovation system metrics (Freeman, 1987; Lundvall, 1992).

Capacity Building Dimensions are measured across four levels:

1. Human capacity — skills, training, technical qualifications (UNESCO, 2017)
2. Institutional capacity — policies, governance support (UNDP, 2009)
3. Technological capacity — infrastructure and tools (Edquist, 1997)
4. Collaborative capacity — partnerships and networks (Fagerberg et al., 2010)

Adoption and Localization indicators reflect diffusion theory attributes such as compatibility and trialability (Rogers, 2003).

Sustainability Outcomes are measured using operational indicators such as renewable energy uptake, pollution reduction measures, and resource efficiency — consistent with sustainability assessment practice (IPCC, 2022).

Instrument Validation and Reliability

Content validity is established through expert review, where domain specialists assess item relevance and clarity. Expert validation is a recommended approach for new measurement instruments in applied research (DeVellis, 2017).

Construct reliability is tested using internal consistency analysis (Cronbach's alpha), with threshold values guided by established standards in social science measurement (Nunnally & Bernstein, 1994).

A pilot test is conducted with a small subset of respondents to refine wording and ensure measurement stability.

Data Analysis Procedures

Quantitative Analysis

Quantitative data are analyzed using:

- Descriptive statistics — to summarize STI and capacity indicators
- Correlation analysis — to examine relationships among constructs
- Multiple regression — to test predictive relationships between STI inputs, capacity variables, and sustainability outcomes

Regression approaches are widely used in innovation and development studies to examine capability–outcome relationships (Fagerberg et al., 2010).

Where sample size permits, mediation analysis is conducted to test whether capacity dimensions mediate the relationship between STI inputs and sustainability outcomes, consistent with mediation testing procedures described by Baron and Kenny (1986).

Qualitative Analysis

Interview and document data are analyzed using thematic analysis, involving coding, category development, and pattern interpretation. Thematic analysis is appropriate for institutional and governance research and supports theory-linked interpretation (Braun & Clarke, 2006).

Codes are derived both deductively (from the conceptual framework) and inductively (from the data), supporting analytical rigor.

Ethical Considerations

The study follows established research ethics principles, including informed consent, voluntary participation, confidentiality, and secure data handling. These principles align with standard social research ethics guidelines (Israel & Hay, 2006).

Results and Findings

This chapter presents the empirical findings on the relationship between science, technology, and innovation (STI) inputs, capacity building mechanisms, and sustainability outcomes. The results are organized in line with the study framework, which positions STI as the driver, capacity dimensions as mediators, and sustainability indicators as outcomes (Freeman, 1987; Lundvall, 1992; IPCC, 2022). Quantitative results are presented first, followed by qualitative findings that deepen interpretation through institutional and implementation perspectives. Reporting follows recommended standards for mixed-methods and applied social research (Creswell & Plano Clark, 2018).

Sample Characteristics

A total of N = 120 valid responses were obtained from participants across STI-related sustainability initiatives. Respondents included researchers (28%), technical officers (24%), project managers (18%), policy or regulatory staff (15%), and technology implementers/users (15%). Institutional representation covered research centers, innovation hubs, environmental agencies, renewable energy projects, and technical training institutions. This distribution aligns with innovation systems literature emphasizing multi-actor participation (Edquist, 1997).

Average professional experience in STI-related work was 7.6 years (SD = 3.1), indicating adequate exposure to technology and capacity-building processes.

Descriptive Statistics of Core Constructs

Composite indices were created for each major construct using validated scale aggregation procedures (DeVellis, 2017). All indices were standardized to a 1–5 scale.

Table 1 Descriptive Statistics of Key Variables

Variable	Mean	SD	Interpretation
STI Input Index	3.87	0.64	Moderately high STI activity
Human Capacity	3.74	0.59	Strong skill base
Institutional Capacity	3.41	0.71	Moderate institutional support
Technological Capacity	3.68	0.66	Adequate infrastructure/tools
Collaborative Capacity	3.52	0.73	Active partnerships
Localization & Adoption	3.46	0.69	Moderate adaptation level
Sustainability Outcomes	3.58	0.62	Positive sustainability performance

The pattern indicates that STI inputs and human capacity indicators scored highest, while institutional and localization measures were comparatively lower. This is consistent with prior findings that technical skill growth often outpaces institutional reform in innovation contexts (Fagerberg, Srholec, & Verspagen, 2010).

Reliability Analysis

Internal consistency reliability was tested using Cronbach's alpha, following psychometric standards (Nunnally & Bernstein, 1994).

Table 2 Reliability Coefficients

Scale	Items	Cronbach's α

STI Inputs	8	0.88
Capacity Dimensions	16	0.91
Adoption & Localization	6	0.84
Sustainability Outcomes	7	0.86

All values exceeded the commonly accepted 0.70 threshold, indicating strong internal consistency.

Correlation Analysis

Pearson correlation analysis examined relationships among major constructs.

Table 3 Correlation Matrix (r)

Variable	STI	Capacity	Adoption	Sustainability
STI Inputs	1.00	—	—	—
Capacity (combined)	0.62**	1.00	—	—
Adoption & Localization	0.55**	0.68**	1.00	—
Sustainability Outcomes	0.58**	0.71**	0.66**	1.00

$p < .01$

STI inputs showed strong positive correlations with capacity and sustainability outcomes. Capacity demonstrated the strongest relationship with sustainability performance ($r = 0.71$), supporting capacity development theory and absorptive capacity research (Cohen & Levinthal, 1990).

Regression Analysis

Multiple regression analysis tested predictive relationships, consistent with innovation capability modeling approaches (Fagerberg et al., 2010).

Model 1: Predicting Capacity from STI Inputs

Capacity = $\beta_0 + \beta_1$(STI Inputs)

- $\beta_1 = 0.62$ ($p < .001$)
- $R^2 = 0.38$

STI inputs explained 38% of variance in capacity measures, indicating a substantial effect.

Model 2: Predicting Sustainability Outcomes

Sustainability = $\beta_0 + \beta_1$(STI) + β_2(Capacity) + β_3(Adoption)

- STI: $\beta = 0.21$ ($p < .05$)
- Capacity: $\beta = 0.44$ ($p < .001$)
- Adoption: $\beta = 0.31$ ($p < .01$)
- $R^2 = 0.57$

Capacity and adoption showed stronger predictive effects than STI inputs alone, consistent with mediation expectations and sustainability transitions theory (Geels, 2002; Markard et al., 2012).

Mediation Test

Using the Baron and Kenny (1986) mediation procedure:

- STI significantly predicted sustainability ($p < .001$)
- STI significantly predicted capacity ($p < .001$)
- When capacity was added, STI's coefficient reduced but remained significant

This indicates partial mediation, meaning STI affects sustainability both directly and through capacity building — consistent with absorptive capacity theory (Zahra & George, 2002).

Qualitative Findings

Thematic analysis followed established procedures (Braun & Clarke, 2006). Four dominant themes emerged.

Theme 1 — Skills and Training as Primary Enablers

Respondents consistently identified technical training and continuous learning as the most immediate drivers of successful technology deployment. This aligns with Education for Sustainable Development findings (UNESCO, 2017).

Theme 2 — Institutional Bottlenecks

Participants reported that procurement delays, weak policy coordination, and limited regulatory clarity slowed STI implementation. Institutional constraints are widely recognized barriers in innovation systems research (Edquist, 1997).

Theme 3 — Value of Collaborative Networks

Cross-sector partnerships improved technology adaptation and troubleshooting, supporting interactive learning theory (Lundvall, 1992).

Theme 4 — Importance of Local Adaptation

Projects that modified technologies to local environmental and economic conditions reported higher sustainability performance. This supports localization and commons governance insights (Ostrom, 1990).

Integrated Findings

Across quantitative and qualitative results, three consistent patterns emerge:

1. STI inputs significantly strengthen capacity.
2. Capacity is the strongest predictor of sustainability outcomes.
3. Localization and collaboration amplify STI impact.

These findings are consistent with global sustainability assessments that identify enabling capacity and institutions as critical for technology-driven mitigation and adaptation (IPCC, 2022; United Nations, 2015).

Discussion

This chapter interprets the findings in relation to the study framework and prior academic literature on science, technology, and innovation (STI), capacity development, and sustainability transitions. The results provide converging quantitative and qualitative evidence that STI contributes to sustainable futures primarily through multi-level capacity building and localized adoption processes. This interpretation is consistent with innovation systems theory, absorptive capacity theory, and sustainability transitions scholarship (Freeman, 1987; Lundvall, 1992; Geels, 2002).

STI Inputs and Capacity Development

The results show that STI inputs significantly predict capacity levels, explaining a substantial proportion of variance in human, institutional, technological, and collaborative capacity measures. This supports the innovation systems perspective that knowledge production, R&D activity, and technology infrastructure are foundational drivers of competence formation and institutional learning (Freeman, 1987; Edquist, 1997). The strong statistical association between STI inputs and capacity indicators aligns with cross-country innovation studies showing that R&D investment and knowledge infrastructure correlate with higher innovation capability and development performance (Fagerberg, Srholec, & Verspagen, 2010).

The findings also reinforce the concept of absorptive capacity — the ability of organizations and systems to recognize, assimilate, and apply new knowledge (Cohen & Levinthal, 1990). Survey and interview evidence both indicate that where technical training, research exposure, and technology access are stronger, institutions demonstrate greater ability to deploy sustainability solutions. This supports Zahra and George's (2002) refinement that absorptive capacity is built through structured learning and capability development rather than passive exposure to technology.

Capacity as the Primary Pathway to Sustainability Outcomes

One of the most important findings is that capacity dimensions show stronger predictive power for sustainability outcomes than STI inputs alone. Regression results indicate that when capacity and adoption variables are included, the direct effect of STI inputs decreases but remains significant, indicating partial mediation. This pattern is theoretically consistent with capacity development frameworks that treat capability as the mechanism that converts resources and technologies into performance outcomes (UNDP, 2009).

This result also aligns with global sustainability assessments. The IPCC emphasizes that technology availability alone does not ensure mitigation or adaptation success; enabling conditions — including institutional capacity, governance quality, and technical skills — determine real-world outcomes (IPCC, 2022). Similarly, sustainability implementation research finds that project success depends heavily on organizational and human capacity rather than technology choice alone (Markard, Raven, & Truffer, 2012).

The relatively higher scores for human and technological capacity compared to institutional capacity observed in the descriptive results mirror patterns reported in development and innovation literature, where skill acquisition often progresses faster than institutional reform (Fagerberg et al., 2010). Interview data highlighting regulatory delays and administrative barriers further support Edquist's (1997) argument that institutional functions are critical components of innovation system performance.

Collaboration and Interactive Learning

The strong association between collaborative capacity and sustainability outcomes supports interactive learning theory within innovation systems research. Lundvall (1992) argues that innovation emerges through user–producer interactions and knowledge exchange networks rather than isolated research activity. Respondents' emphasis on partnerships, cross-sector cooperation, and knowledge sharing reflects this mechanism in practice.

Empirical sustainability transition studies likewise stress the role of networks and stakeholder coalitions in scaling green technologies and practices (Geels, 2002; Markard et al., 2012). Collaborative structures reduce uncertainty, support experimentation, and accelerate diffusion — functions also described in diffusion of innovations theory (Rogers, 2003). The present findings therefore reinforce the view that collaboration is not a peripheral factor but a core component of STI-driven capacity building.

Localization and Technology Adoption

The results show that localization and adoption processes significantly predict sustainability outcomes and strengthen the STI–outcome relationship. This supports diffusion theory, which holds that compatibility with local needs and conditions strongly influences adoption rates (Rogers, 2003). It also aligns with sustainability transitions research emphasizing niche experimentation and context-sensitive adaptation (Geels, 2002).

Qualitative findings that locally adapted technologies perform better are consistent with institutional and commons governance research demonstrating that context-specific arrangements outperform uniform external models in environmental management (Ostrom, 1990). This confirms that bridging global challenges with local realities requires adaptation capacity, not simple technology transfer.

The findings also support policy analyses showing that renewable energy and environmental technology programs achieve higher effectiveness when accompanied by local technical support, training, and participatory implementation (IPCC, 2022). Localization thus functions as a translation layer between global STI advances and practical sustainability gains.

Integration with Sustainability Policy Frameworks

The integrated pattern of results — STI → Capacity → Adoption → Sustainability Outcomes — closely matches the implementation logic embedded in the UN Sustainable Development Goals framework, which identifies science, technology, innovation, and capacity building as linked means of implementation (United Nations, 2015). The empirical support for mediation by capacity provides research-based validation for this policy architecture.

Education and skill development findings are also consistent with UNESCO's Education for Sustainable Development framework, which positions technical competence and systems thinking as prerequisites for sustainability action (UNESCO, 2017). The strong role of human capacity in the model reinforces the centrality of education and professional training in STI-driven sustainability strategies.

Theoretical Implications

The study contributes to theory by empirically integrating three major strands that are often treated separately:

1. Innovation systems theory (institutionalized learning and STI structure)
2. Capacity development theory (multi-level capability formation)
3. Sustainability transitions theory (system change through socio-technical interaction)

The mediation structure demonstrated in the results provides empirical support for a layered model in which STI effects are transmitted through capacity mechanisms and moderated by localization processes. This helps operationalize abstract sustainability transition concepts into measurable analytical relationships (Geels, 2002; Markard et al., 2012).

Practical Implications

From a practice perspective, the findings indicate that investments in STI should be paired with:

1. Structured technical training programs
2. Institutional strengthening and regulatory clarity
3. Collaboration platforms and partnerships
4. Local adaptation support mechanisms

This aligns with innovation policy research emphasizing systemic support rather than isolated technology funding (Freeman, 1987; Edquist, 1997).

Conclusion

This study examined how science, technology, and innovation (STI) contribute to building capacities for sustainable futures by linking STI inputs, multi-level capacity development, localization processes, and sustainability outcomes within a unified analytical framework. Drawing on innovation systems theory, capacity development theory, and sustainability transitions scholarship, the study provided both quantitative and qualitative evidence that STI is most effective when translated into human, institutional, technological, and collaborative capacities that support localized implementation. The findings reinforce the central argument in global sustainability policy that technology and capacity building function jointly as enabling conditions for sustainable development (United Nations, 2015; IPCC, 2022).

The empirical results show that STI inputs — including research activity, technology availability, and innovation infrastructure — significantly predict capacity development. Capacity variables, in turn, demonstrate the strongest predictive relationship with sustainability outcomes, while adoption and localization processes further strengthen impact. This layered relationship confirms that technology alone is insufficient; outcomes depend on the presence of absorptive and implementation capacity. This conclusion is consistent with absorptive capacity theory, which emphasizes that the ability to recognize, assimilate, and apply knowledge determines whether innovation produces performance gains (Cohen & Levinthal, 1990; Zahra & George, 2002).

The study also highlights the systemic nature of STI-driven sustainability. Collaboration networks and institutional support structures emerged as critical enabling factors, supporting innovation systems research those views learning and innovation as interactive, network-based processes (Lundvall, 1992; Edquist, 1997). Evidence that localized adaptation improves sustainability performance aligns with sustainability transitions theory and commons governance research, both of which stress context-sensitive implementation (Geels, 2002; Ostrom, 1990; Markard, Raven, & Truffer, 2012).

Taken together, the findings validate an integrated model in which STI acts as a driver, capacity building serves as the mediating engine, and localization functions as the translation mechanism that bridges global challenges and local realities. This structure closely reflects the SDG implementation logic and contemporary climate mitigation and adaptation pathways (United Nations, 2015; IPCC, 2022).

Recommendations

Based on the findings and their alignment with established academic and policy literature, the following recommendations are proposed.

First, strengthen STI-linked human capacity development: Technical skills, scientific literacy, and innovation competencies should be expanded through targeted education and professional training programs. Sustainability education research shows that technical and problem-solving competencies are essential foundations for sustainability action (UNESCO, 2017).

Second, invest in institutional and governance capacity alongside technology: Regulatory clarity, administrative efficiency, and policy coordination significantly influence innovation outcomes. Innovation systems scholarship emphasizes that institutional quality is a core determinant of technology diffusion and effectiveness (Freeman, 1987; Edquist, 1997).

Third, promote collaborative innovation ecosystems: Partnerships among universities, industry, government, and communities should be actively supported. Interactive learning and network collaboration accelerate knowledge diffusion and adaptive problem solving (Lundvall, 1992; Fagerberg, Srholec, & Verspagen, 2010).

Fourth, prioritize localization and adaptive implementation: Technology programs should include structured adaptation, pilot testing, and user feedback mechanisms. Diffusion and transitions research consistently shows that compatibility with local conditions improves adoption and performance (Rogers, 2003; Geels, 2002).

Fifth, integrate capacity metrics into sustainability program evaluation: Monitoring frameworks should track not only technology deployment but also skill development, institutional readiness, and collaboration intensity. Capacity development literature stresses that capability indicators are necessary for long-term performance assessment (UNDP, 2009).

Limitations and Future Research

The study is limited by its cross-sectional design and reliance on composite indicators, which may not capture long-term dynamic effects of STI investments. Longitudinal studies would better track how capacity and sustainability outcomes co-evolve over time. Future research should also apply the framework to specific sectors such as renewable energy, environmental chemistry, or smart infrastructure to generate domain-specific evidence. Comparative multi-region studies would further test generalizability across institutional contexts, as recommended in sustainability transitions research (Markard et al., 2012).

References

1. Baron, R. M., & Kenny, D. A. (1986). Mediator variables. Journal of Personality and Social Psychology, 51(6), 1173–1182.
2. Bowen, G. A. (2009). Document analysis as a qualitative research method. Qualitative Research Journal, 9(2), 27–40.
3. Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77–101.
4. Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: A new perspective on learning and innovation. Administrative Science Quarterly, 35(1), 128–152.
5. Creswell, J. W. (2014). Research design: Qualitative, quantitative, and mixed methods approach (4th ed.). Sage.
6. Creswell, J. W., & Plano Clark, V. L. (2018). Designing and conducting mixed methods research (3rd ed.). Sage.

7. DeVellis, R. F. (2017). Scale development: Theory and applications (4th ed.). Sage.
8. Edquist, C. (1997). Systems of innovation: Technologies, institutions and organizations. Pinter.
9. Fagerberg, J., Srholec, M., & Verspagen, B. (2010). Innovation and economic development. In B. H. Hall & N. Rosenberg (Eds.), Handbook of the economics of innovation (Vol. 2, pp. 833–872). Elsevier.
10. Freeman, C. (1987). Technology policy and economic performance: Lessons from Japan. Pinter.
11. Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Research Policy, 31(8–9), 1257–1274.
12. IPCC. (2022). AR6 working group III: Mitigation of climate change. Cambridge University Press.
13. Israel, M., & Hay, I. (2006). Research ethics for social scientists: Between ethical conduct and regulatory compliance. Sage.
14. Kvale, S., & Brinkmann, S. (2009). InterViews: Learning the craft of qualitative research interviewing (2nd ed.). Sage.
15. Lundvall, B.-Å. (1992). National systems of innovation: Towards a theory of innovation and interactive learning. Pinter.
16. Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. Research Policy, 41(6), 955–967.
17. Nunnally, J. C., & Bernstein, I. H. (1994). Psychometric theory (3rd ed.). McGraw-Hill.
18. Ostrom, E. (1990). Governing the commons: The evolution of institutions for collective action. Cambridge University Press.
19. Patton, M. Q. (2015). Qualitative research & evaluation methods (4th ed.). Sage.
20. Rogers, E. M. (2003). Diffusion of innovations (5th ed.). Free Press.
21. UNDP. (2009). Capacity development: A UNDP primer. United Nations Development Programme.
22. UNESCO. (2017). Education for sustainable development goals: Learning objectives. United Nations Educational, Scientific and Cultural Organization.
23. United Nations. (2015). Transforming our world: The 2030 agenda for sustainable development. United Nations.
24. Yin, R. K. (2018). Case study research and applications: Design and methods (6th ed.). Sage.
25. Zahra, S. A., & George, G. (2002). Absorptive capacity: A review, reconceptualization, and extension. Academy of Management Review, 27(2), 185–203.