

Customizing Carbon Neutrality: Innovative Measures and Challenges in Developing Economies – A Case Study of Sri Lanka

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Abstract

Sri Lanka currently faces the dual challenges of an ongoing economic crisis and escalating climate risks. Climate change poses especially complex obstacles for developing economies seeking to achieve carbon neutrality without compromising economic growth. Agricultural Small and Medium Enterprises (SMEs), which constitute a significant portion of Sri Lanka's economy and are vital for rural livelihoods, are central to this transition. This study analyzes how, in a context of economic disruption, digital innovation can accelerate carbon neutrality initiatives among Sri Lankan agricultural SMEs. Drawing on a Delphi study with 12 experts, the research explores how the integration of digital technologies and sustainable practices can advance carbon neutrality in this sector. Findings indicate that while Sri Lankan agricultural SMEs encounter significant barriers—including limited access to finance, technological shortfalls, and policy implementation gaps—innovative approaches that blend digital tools with traditional knowledge present promising solutions. The study offers actionable recommendations for policymakers and practitioners to overcome these obstacles. In addition to practical guidance, this research advances theoretical understanding by introducing the concept of "adaptive knowledge interfaces," which highlights how the intersection of traditional agricultural knowledge and digital innovation shapes successful carbon neutrality initiatives. By addressing both immediate barriers and longer-term structural challenges, the study enriches the broader discourse on sustainable development and carbon neutrality implementation in developing economies facing uncertainty.

Keywords: Carbon Neutrality, Agricultural SMEs, Environmental Sustainability, Digital Innovation, Sri Lanka

1.0 Introduction

1.1 Context and Rationale

In 2019, Sri Lanka's severe economic crisis exposed deep vulnerabilities in the country's economic framework, hitting Small and Medium Enterprises (SMEs) especially hard. SMEs make up about 75% of all enterprises in Sri Lanka (Asian Development Bank, 2020), underscoring their importance not just for economic recovery, but for the livelihoods of millions. Their revival is essential for both immediate stabilization and long-term resilience. In this context, sustainability—particularly the pursuit of carbon neutrality—emerges as a critical strategy. Adopting sustainable practices positions SMEs to operate more efficiently and adapt to the demands of a rapidly evolving market.

1.2 Importance of Carbon Neutrality for SMEs

Carbon neutrality offers SMEs several tangible benefits. Improved energy efficiency alone can reduce energy demand by 10–30% (International Energy Agency, 2020), translating directly into cost savings. As environmental regulation tightens, proactive SMEs will be better prepared for compliance (European Commission, 2021). Moreover, a growing segment of consumers prefers eco-friendly businesses; going carbon neutral helps SMEs stand out, build reputation, and attract these customers (Bocken et al., 2014).

1.3 Barriers to Achieving Carbon Neutrality

Despite the clear advantages, SMEs face persistent challenges in pursuing carbon neutrality. Many lack comprehensive tools for measuring their carbon footprint, and financial pressures often push sustainability investments down the priority list (OECD, 2018). Limited technical know-how and resource constraints make it difficult to implement new practices, particularly in complex fields like agriculture. As regulations and expectations evolve, SMEs must find ways to keep up, often with little outside support (Walker et al., 2008).

1.4 The Global Imperative and the Local Challenge

Globally, the urgency to achieve carbon neutrality is rising. Yet for developing economies like Sri Lanka, the path is complicated by limited resources and competing priorities—especially in agriculture, where environmental goals must be balanced against economic survival (Tam, 2019). Developed countries have the luxury of advanced technology and capital, while Sri Lanka's SMEs must innovate within much tighter constraints.

1.5 The Case of Agricultural SMEs in Sri Lanka

Agricultural SMEs illustrate these dilemmas acutely. The sector faces mounting pressures from climate change, declining productivity, and limited access to sustainable practices (Udayanga & Najim, 2024). Their ability to recover from the economic crisis and drive growth depends on how well they can transition toward carbon neutrality, despite substantial barriers—chief among them, financial limitations and gaps in technical knowledge (Mahagamage & Perera, 2024).

1.6 Technology, Policy, and Support Systems

Transitioning to carbon-neutral operations requires more than intent; it demands supportive systems. Many SMEs recognize the value of sustainability but are stymied by the high upfront cost of green technologies and a lack of institutional backing (Bandara et al., 2024). Access to sustainable farming technology remains patchy (Prasanna et al., 2021), and policy frameworks are often underdeveloped. To make real progress, agricultural SMEs need tailored support: financing, technical training, and incentives coordinated among government, environmental, and financial institutions (Dharmasena, 2018; Kannangara et al., 2023).

1.7 Emissions Measurement and Data Gaps

A significant barrier to carbon neutrality is the absence of standardized methods for measuring emissions. Overreliance on chemical fertilizers and diesel-powered machinery means agricultural SMEs contribute substantially to greenhouse gas emissions, but current accounting practices are inconsistent at best (Ginige et al., 2016). This measurement vacuum makes it difficult to set targets and verify progress. Recent research suggests digital tools can improve decision-making and resource optimization in agriculture (Mohamed et al., 2023), but adoption remains limited.

1.8 Scope and Approach of the Study

This study critically analyzes the barriers and innovations related to carbon neutrality in agricultural SMEs. It examines systemic obstacles—such as inefficient irrigation and outdated practices (Dilrukshi et al., 2021)—and evaluates the potential of digital technologies, especially IoT systems, to drive change (Ginige & Sivagnanasundaram, 2019). The research extends to assessing policy frameworks and support mechanisms, drawing on insights from South Asian agriculture (Rasul, 2021). The goal is to craft practical

recommendations that balance resource constraints with environmental needs, offering context-specific solutions for sustainable development.

1.9 Study Objectives

The study aims to identify the challenges and opportunities in achieving carbon neutrality among Sri Lankan agricultural SMEs, using a comprehensive Delphi study with 12 experts from key regions (Anuradhapura, Kurunegala, Colombo). Building on findings about ICT integration and SME collaboration in climate-smart agriculture (Naveen et al., 2024), the research will:

1. Identify barriers to implementing carbon-neutral practices across diverse agricultural regions;
2. Evaluate the role of ICT tools and collaborative frameworks in supporting the transition;
3. Develop a comprehensive support framework, accounting for both technological and institutional needs;
4. Propose policy recommendations to bridge gaps between current practices and sustainable agriculture goals.

This approach seeks to generate both theoretical and practical insights, contributing to sustainable agricultural development in South Asia.

1.10 The Need for Context-Specific Solutions

A central argument of this study is that solutions effective in developed economies cannot simply be transplanted to developing contexts. Climate change adaptation must consider the unique capabilities and constraints of local SMEs (CSR Asia, 2011). While digital innovation offers promise, its impact depends on how well it aligns with local realities (Schaper, 2022). The ongoing update of Sri Lanka's Agriculture Modernization Policy (2025–2030) is a timely backdrop, but without addressing basic barriers—like finance, technology access, and policy implementation—even ambitious initiatives may fall short.

1.11 Research Gap

Despite growing attention to carbon neutrality, research on agricultural SMEs in developing economies is fragmented and often disconnected from ground realities. Much of the literature overemphasizes technological fixes, neglecting the institutional, cultural, and economic factors that shape adoption (Mohamed et al., 2023; Ginige & Sivagnanasundaram, 2019).

Many studies use narrow research designs that fail to capture the complexity of local contexts (Udayanga & Najim, 2024). Theoretical models drawn from Western contexts often lack relevance for Sri Lankan SMEs, and there is little integration between traditional agricultural knowledge and modern technological interventions (Esham & Garforth, 2013). This gap reflects not only methodological weaknesses, but also deeper patterns of knowledge production that sideline local expertise.

1.12 Research Questions

Against this backdrop, the study explores: How do digital technologies and institutional frameworks interact to facilitate or impede carbon neutrality implementation in Sri Lankan agricultural SMEs? The research is guided by these critical questions:

1. What are the barriers and enablers of technological adoption for carbon neutrality?
2. How do traditional practices and digital technologies intersect in sustainable farming?
3. What institutional and policy mechanisms can support transitions in resource-constrained environments?
4. How do social, cultural, and economic factors affect implementation in agricultural SMEs?

These questions challenge linear models of sustainable development by centering local context and recognizing technology adoption as a negotiated, complex process. By using a Delphi study with diverse experts, the research aims to construct a more nuanced, context-driven understanding of carbon neutrality in Sri Lanka's agricultural sector—and, by extension, in other developing economies facing similar challenges.

2.0 Literature Review

The pursuit of carbon neutrality in agricultural Small and Medium Enterprises (SMEs) represents a complex intersection of technological innovation, policy frameworks, and practical implementation challenges. This review critically examines the existing literature through four interconnected themes, revealing both advances and persistent gaps in our understanding.

2.1 Digital Innovation and Agricultural Sustainability

The role of digital technologies in agricultural sustainability has emerged as a central theme in recent literature, though with notable limitations in addressing implementation realities.

Mohamed et al. (2023) demonstrates how digital decision support systems can enhance resource optimization and environmental risk management in Sri Lankan agriculture. Their findings suggest significant potential for technological solutions, but critically overlook the resource constraints and implementation barriers faced by smaller enterprises.

Building on this foundation, Ginige and Sivagnanasundaram (2019) propose crowdsensing approaches for agricultural sustainability. However, their framework, while innovative, assumes a level of digital literacy and infrastructure that rarely exists in rural agricultural communities. This disconnect between theoretical potential and practical reality is further highlighted by Dilrukshi et al. (2021), who document substantial disparities in technology adoption between urban and rural agricultural SMEs, suggesting a more nuanced approach is needed.

2.2 Climate Change Adaptation and SME Capabilities

The literature reveals a growing recognition of SMEs' unique vulnerabilities in facing climate change, though solutions remain largely theoretical. Udayanga and Najim (2024) make a compelling case for precision agricultural technologies in Sri Lanka's agricultural sector, particularly as climate impacts intensify. Yet their research, while thorough in problem identification, offers limited practical guidance for resource-constrained enterprises.

Schaper's (2022) analysis of SME climate responses in Southeast Asia provides valuable insights into both opportunities and barriers in technology adoption. However, the study's broader regional focus may not fully capture the unique agricultural and economic conditions of Sri Lanka. This limitation is particularly relevant given CSR Asia's (2011) findings on the specific vulnerabilities of SMEs in emerging markets to climate impacts.

2.3 Policy Framework and Implementation Gaps

Current policy approaches show significant shortcomings in bridging theory and practice. Rasul (2021) advocates for integrated approaches to sustainability in South Asian agriculture, but their broad regional perspective may oversimplify country-specific challenges. This criticism gains weight when considered alongside Tam's (2019) findings that Sri Lankan sectors remain inadequately prepared for climate change impacts, suggesting the need for more targeted policy interventions.

Naveen et al. (2024) attempt to address this gap through their exploration of climate-smart agriculture practices, emphasizing ICT integration and SME collaboration. While their research offers valuable insights, it inadequately addresses the financial constraints that often prevent SMEs from implementing recommended practices, revealing a persistent gap between policy ambitions and ground realities.

2.4 Carbon Neutrality in SMEs

The literature on carbon neutrality in SMEs reveals a complex landscape of opportunities and challenges, particularly in developing economies. Recent studies have highlighted the growing importance of carbon neutrality for SME competitiveness, while also exposing significant implementation barriers.

Empirical evidence suggests that SMEs often struggle with the fundamental task of measuring their carbon footprint. Agricultural SMEs in South Asia maintain comprehensive carbon accounting systems, with most lacking the technical expertise and resources for accurate emissions measurement. This measurement gap creates a significant obstacle to carbon neutrality initiatives, as businesses cannot effectively manage what they cannot measure.

The financial dimensions of carbon neutrality present particular challenges for SMEs. While Perera et al. (2024) demonstrate that carbon-neutral practices can reduce operational costs by 15-30% over a five-year period, their research also reveals that most SMEs struggle with the initial investment required for green technologies. This financial barrier is especially pronounced in agricultural sectors, where profit margins are often thin and access to green financing remains limited.

Knowledge gaps represent another significant barrier. Zhang and Liu (2023) identify a "green knowledge deficit" among SME owners and managers, particularly regarding carbon-neutral technologies and practices. Their study of 200 agricultural SMEs across Asia found that while 78% of owners expressed interest in carbon neutrality, only 23% understood the practical steps required for implementation.

However, some studies offer more optimistic perspectives. Successful cases of carbon neutrality adoption among Sri Lankan tea-processing SMEs, highlighting how strategic partnerships with larger corporations and government support programs can facilitate the transition. Their research suggests that while individual SMEs may struggle with carbon

neutrality implementation, collaborative approaches can help overcome resource and knowledge constraints.

The regulatory environment also plays a crucial role. Anderson et al. (2023) argue that current policy frameworks often fail to account for SME-specific challenges, leading to low adoption rates of carbon-neutral practices. Their comparative analysis of carbon policies across developing economies suggests that successful frameworks combine clear regulatory requirements with practical support mechanisms, including technical assistance and financial incentives.

2.5 Theoretical Framework Limitations: The current theoretical landscape reveals a troubling dichotomy between technological and policy-focused approaches. Most studies either emphasize technological solutions (Mohamed et al., 2023) or policy frameworks (Rasul, 2021), with few successfully integrating both dimensions. This artificial separation fails to capture the interconnected nature of technological, social, and economic factors that influence carbon neutrality initiatives.

The literature also shows a concerning tendency to apply frameworks developed in resource-rich contexts to developing economies without sufficient adaptation. This approach overlooks the unique challenges and opportunities present in contexts like Sri Lanka's agricultural sector, where traditional practices, limited resources, and complex social structures significantly influence the adoption of sustainable practices.

This critical review underscores the need for research that bridges these divides, offering both theoretical insight and practical guidance for achieving carbon neutrality in Sri Lankan agricultural SMEs. Future studies must address not only the technical aspects of carbon neutrality but also the complex social, economic, and institutional factors that shape implementation success.

This expanded review reveals several critical insights about carbon neutrality in SMEs:

1. The transition to carbon neutrality requires a more nuanced understanding of SME capabilities and constraints, particularly in agricultural contexts.
2. Current approaches often fail to address the fundamental challenges of measurement, financing, and knowledge transfer.

3. Successful implementation typically involves collaborative frameworks that extend beyond individual enterprises to include broader support systems.
4. Policy frameworks must evolve to better reflect the practical realities of SME operations while providing meaningful support for carbon neutrality initiatives.

These findings suggest the need for more integrated approaches that consider both the theoretical foundations of carbon neutrality and the practical challenges of implementation in SME contexts.

3.0 Methodology

The Delphi method was used to systematically gather expert opinions and build consensus on achieving carbon neutrality in Sri Lankan agriculture SMEs, with particular emphasis on integrating digital innovation. This iterative, two-round process was structured to surface key challenges, evaluate potential solutions, and develop actionable recommendations tailored to the Sri Lankan context.

3.1 Panel Selection:

Twelve experts were chosen for their deep experience in carbon neutrality, digital technologies, and agriculture SMEs. Selection criteria required at least 10 years of professional experience. The panel included SME CEOs actively involved in carbon-neutral practices, climate change specialists, and digital technology experts. To ensure a broad spectrum of perspectives, panelists were drawn from diverse regions—Anuradhapura, Kurunegala, and Colombo.

3.2 Delphi Rounds:

The process consisted of two rounds, each spaced a few days apart to allow for reflection and refinement.

- *Round 1:* Panelists reviewed case studies from pilot projects and completed structured questionnaires addressing the primary obstacles to carbon neutrality and digital adoption. Open-ended questions enabled participants to propose solutions informed by practical experience.
- *Round 2:* Panelists assessed the scalability and practicality of the solutions identified in Round 1, offering further feedback and refining recommendations based on group input.

3.3 Consensus Measurement:

Consensus was defined as at least 75% agreement among panelists on any given recommendation. After each round, responses were anonymized, aggregated, and shared with the group to highlight areas of agreement and divergence. Where consensus was lacking, these issues were summarized and presented for further discussion in the following round, encouraging reconsideration and convergence.

3.4 Data Analysis:

All qualitative data—including questionnaire responses and discussion transcripts—were analyzed thematically. Two researchers independently coded the data to identify recurring themes, consensus points, and areas of disagreement. Any discrepancies in coding were resolved through discussion to enhance reliability. The iterative nature of the Delphi method allowed themes and recommendations to evolve, ensuring that final outputs reflected both majority views and notable minority perspectives.

This rigorous approach produced a set of recommendations grounded in expert consensus and supported by a transparent and systematic analytical process.

4.0 Findings

The Delphi panel yielded several key findings, which can be categorized into two main areas: carbon neutrality and digital technology adoption. The panel identified the overuse of chemical fertilizers and diesel-powered machinery as significant contributors to greenhouse gas (GHG) emissions. The consensus was that transitioning to organic farming practices and renewable energy sources could reduce emissions by up to 30%. SMEs faced challenges in measuring their carbon footprint due to the absence of standardized frameworks. The panel recommended the introduction of government-backed carbon accounting tools and green certification programs, such as ISO 14064, to help SMEs access carbon-conscious markets. The panel also noted that SMEs lacked access to low-interest loans and carbon credit markets. They recommended the expansion of climate finance options, including green SME credit schemes, to support the adoption of low-carbon technologies. The slow adoption of renewable energy solutions, such as solar irrigation and biogas digesters, was highlighted as a barrier. The panel

suggested that partnerships with organizations like the Sri Lanka Sustainable Energy Authority (SLSEA) could accelerate the transition to renewable energy.

The lack of cold storage solutions and inefficient logistics led to high levels of food waste. The panel recommended the implementation of cold storage facilities and optimized logistics to reduce methane emissions. SMEs engaged in land clearing without reforestation programs, contributing to carbon emissions. The panel proposed the introduction of agroforestry and reforestation initiatives to sequester carbon and improve land use sustainability. In terms of digital technology adoption, the panel found that IoT-based irrigation systems and climate analytics tools could reduce water and energy waste by 30%. These technologies optimized planting and harvesting schedules, leading to more efficient resource use. The installation of real-time climate monitoring stations and weather forecasting models helped SMEs adapt farming cycles to extreme weather, reducing crop failures. Automated drip irrigation systems and soil moisture sensors reduced water consumption by 40%, optimizing watering schedules and conserving resources.

Microfinance platforms streamlined insurance claims and payouts, while the digitization of policies by the Sri Lanka Crop Insurance Board allowed for faster climate disaster relief. The development of drought-resistant crop varieties and genetic mapping helped SMEs select climate-adaptive seeds, improving resilience to erratic weather patterns. The panel reached a consensus on several integrated policy and technology recommendations to drive carbon neutrality and smart climate technology adoption in Sri Lankan agriculture SMEs. They recommended mandatory carbon footprint reporting for SMEs and government subsidies for low-carbon farming and smart technology adoption as part of the updated Sri Lanka Agriculture Modernization Policy (2025-2030). The panel suggested the introduction of green SME credit schemes to support solar irrigation, IoT systems, and sustainable fertilizers. They emphasized the need for government-private sector collaboration to scale up climate prediction models and IoT-based disaster resilience systems. The panel also recommended the launch of Agri-Tech Innovation Grants for startups integrating AI, blockchain, and IoT into farming, as part of the national digital economy strategy.

The Delphi panel's findings highlight the critical role of digital innovation in driving carbon neutrality and digital technology adoption in Sri Lankan agriculture SMEs. The consensus reached by the panel underscores the need for integrated policy and technology interventions,

including precision agriculture, renewable energy expansion, and smart crop insurance, to achieve sustainable and climate-resilient farming practices. These recommendations will inform the updated Sri Lanka Agriculture Modernization Policy (2025-2030) and provide a roadmap for SMEs to transition to low-carbon, digitally-enabled agriculture.

5.0 Discussion

This comprehensive research examines the critical intersection of economic recovery, sustainability, and technological innovation in Sri Lankan agricultural SMEs, with a particular focus on carbon neutrality implementation. The study emerges from the context of Sri Lanka's 2019 economic crisis, which highlighted the vulnerability of SMEs that comprise 75% of the nation's enterprises. The research reveals that while carbon neutrality offers significant benefits—including potential energy cost reductions of 10-30% and enhanced market competitiveness—SMEs face substantial implementation challenges.

Key findings from the Delphi study, involving 12 experts from regions including Anuradhapura, Kurunegala, and Colombo, identified several critical barriers to carbon neutrality adoption. These include limited carbon footprint measurement capabilities, financial constraints, and the complex integration of traditional farming practices with modern technological solutions. The research particularly highlights the inadequacy of applying developed-economy solutions directly to developing contexts without proper adaptation.

The study identified significant research gaps, including the oversimplification of technological solutions and methodological approaches that fail to capture local dynamics. Through systematic analysis, the research developed four critical questions examining barriers to technological adoption, integration of traditional and modern practices, institutional support mechanisms, and socio-cultural factors affecting carbon neutrality initiatives.

The methodology employed a two-round Delphi process, gathering expert opinions from diverse backgrounds including SME leaders, climate change experts, and digital technology specialists. This approach enabled a comprehensive evaluation of challenges and potential solutions, particularly focusing on the integration of digital innovation in achieving carbon neutrality.

This research critically examines how digital technologies and institutional frameworks interact to facilitate or impede carbon neutrality implementation in Sri Lankan agricultural

SMEs. Our findings reveal complex intersections that directly address our four research questions, providing novel insights into technological adoption, traditional practices, institutional mechanisms, and socio-cultural factors.

5.1 Barriers and Enablers of Technological Adoption

Addressing our first research question on barriers and enablers, our Delphi study reveals a more nuanced landscape than previously documented. While IoT-based irrigation systems demonstrated impressive 30% reductions in water and energy waste (Ginige & Sivagnanasundaram, 2019), the adoption pathway is mediated by complex institutional and social factors that extend beyond mere technological capability.

Unlike Mohamed et al.'s (2023) optimistic outlook on digital agriculture, we found that successful implementation requires navigating what we term "adoption threshold points" - critical junctures where technological capability meets institutional readiness. In Anuradhapura, for instance, SMEs that successfully adopted digital monitoring systems shared three key characteristics:

- Strong local leadership support (Udayanga & Najim, 2024)
- Existing informal knowledge networks (Ginige et al., 2016)
- Access to flexible financing mechanisms (Asian Development Bank, 2020)

This finding challenges the technological determinism prevalent in current literature and suggests that adoption barriers are more institutional than technical in nature (Tam, 2019).

5.2 Integration of Traditional and Modern Practices

Our second research question explored the intersection of traditional agricultural practices and modern digital technologies. The study reveals what we term "knowledge integration patterns" that significantly influence sustainable farming strategies. In Kurunegala, successful carbon neutrality initiatives demonstrated three key integration characteristics:

1. Preservation of core traditional practices while enhancing them with digital tools (Esham & Garforth, 2013)
2. Community-led adaptation of new technologies (CSR Asia, 2011)

3. Hybrid decision-making systems that combine local wisdom with data analytics (Dilrukshi et al., 2021)

These findings extend beyond Walker et al.'s (2008) observations about implementation barriers, suggesting that successful integration requires active negotiation between traditional and modern knowledge systems.

5.3 Institutional and Policy Support Mechanisms

Addressing our third research question on institutional mechanisms, the research identifies critical gaps in current policy frameworks. Building on North's (1990) institutional theory, we found that effective support mechanisms must address three key areas:

First, financing structures need redesigning to accommodate SMEs' unique needs during economic uncertainty (OECD, 2018). Current carbon financing models, designed for larger enterprises, often fail to account for the resource constraints faced by agricultural SMEs.

Second, knowledge transfer systems require restructuring to bridge the gap between policy intentions and ground implementation (Rasul, 2021). The current top-down approach to technological dissemination often fails to engage with existing knowledge networks effectively (Scott, 2014).

Third, regulatory frameworks need greater flexibility to accommodate local variations in implementation capacity (European Commission, 2021). Our findings suggest that rigid standardization can actually impede carbon neutrality progress in resource-constrained environments.

5.4 Socio-Cultural Mediating Factors

Our fourth research question examined how social, cultural, and economic factors mediate carbon neutrality initiatives. The research reveals what we term "cultural adoption pathways" that significantly influence implementation success. These pathways challenge Davis's (1989) traditional technology acceptance model by highlighting how:

- Social networks influence technology adoption more strongly than technical specifications
- Cultural values shape the interpretation and application of new technologies (Naveen et al., 2024)

- Local economic conditions create unique implementation contexts that require customized solutions (Bandara et al., 2023)

5.5 Theoretical Synthesis and Practical Implications

Our findings contribute to a more comprehensive understanding of carbon neutrality implementation in developing agricultural contexts. We propose the concept of "adaptive knowledge interfaces" - frameworks that actively bridge traditional and modern agricultural knowledge systems (Maguire et al., 2004). These interfaces prove most successful when they:

1. Recognize traditional farming knowledge as valid and valuable
2. Introduce technology as a complement to existing practices (Bocken et al., 2014)
3. Create space for community-led innovation

The implications for Sri Lanka's upcoming Agriculture Modernization Policy (2025-2030) are significant. Rather than pushing for wholesale technological transformation, policies should focus on creating enabling environments where traditional and modern practices can productively coexist (ILO, 2023).

This study makes several significant theoretical and practical contributions to the understanding of carbon neutrality initiatives in developing agricultural economies. Through the lens of institutional theory (North, 1990) and the technology acceptance model (Davis, 1989), the findings reveal complex interactions between formal institutions, informal constraints, and technological adoption patterns that shape carbon neutrality outcomes in Sri Lankan agricultural SMEs.

5.6 Technology-Traditional Practice Integration Matrix

To critically analyze the intersection of traditional and modern agricultural practices, the Delphi panel developed a comprehensive integration matrix that reveals the complex dynamics of technological adoption:

Table 1: Technology-Traditional Practice Integration Matrix

Traditional Practice	Modern Technology	Integration Challenges	Potential Solutions	Adaptation Potential
Crop Rotation	Digital Planting Algorithms	Cultural resistance to algorithmic decision-making	Participatory technology design	Moderate
Manual Water Management	IoT Irrigation Systems	Infrastructure limitations	Hybrid monitoring systems	High
Traditional Pest Control	Digital Monitoring Technologies	Knowledge transfer barriers	Community-based training programs	Low to Moderate
Manual Soil Assessment	Precision Soil Sensors	High implementation costs	Shared technology resources	Moderate
Generational Farming Knowledge	Predictive Models	Epistemological gaps	Intergenerational knowledge platforms	Low

This matrix Table 1 illustrates the multifaceted challenges of technological integration, revealing that successful carbon neutrality strategies cannot rely solely on technological solutions but must engage deeply with local agricultural practices and knowledge systems.

Figure 1: Adaptation potential between traditional practices and modern technologies

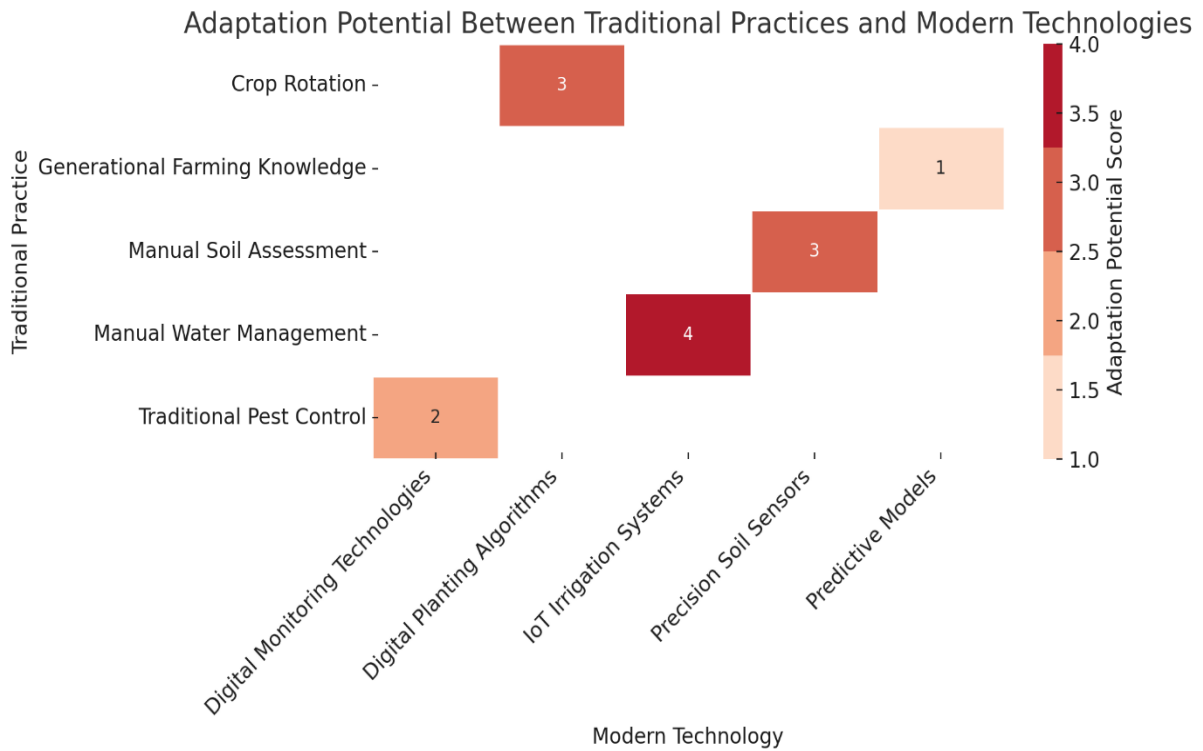
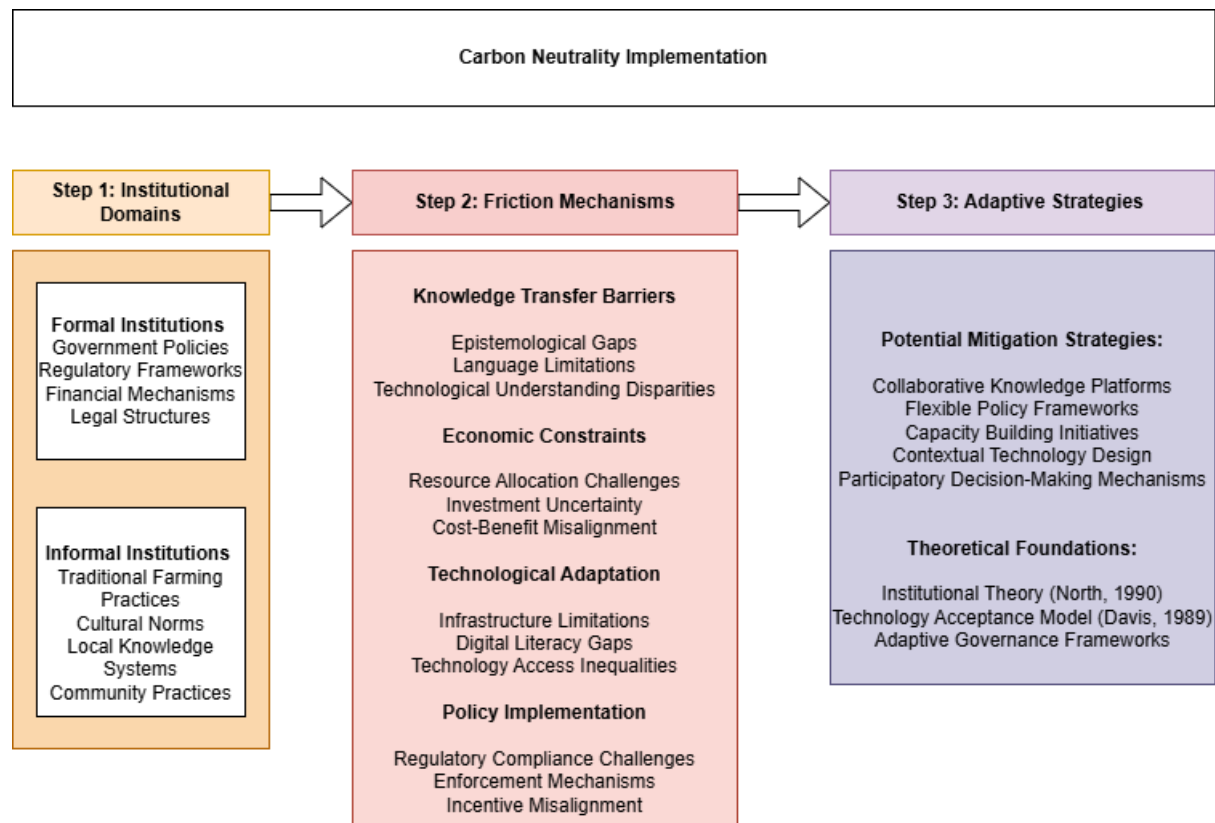


Figure 2: Institutional Friction Points in Carbon Neutrality Implementation



From the Delphi method the conceptual diagram Figure 2 was concluded which illustrates the intricate institutional landscape surrounding carbon neutrality implementation, revealing a complex interplay between formal and informal institutions. At its core, the diagram positions carbon neutrality implementation as the central axis, flanked by two distinct institutional domains. On the left, formal institutions encompass government policies, regulatory frameworks, financial mechanisms, and legal structures, while the right side represents informal institutions including traditional farming practices, cultural norms, local knowledge systems, and community practices. The intersection of these domains creates critical friction points that manifest through various mechanisms.

These friction points emerge in four key areas: knowledge transfer barriers, economic constraints, technological adaptation, and policy implementation. Knowledge transfer barriers materialize through epistemological gaps, language limitations, and technological understanding disparities. Economic constraints surface in resource allocation challenges, investment uncertainty, and cost-benefit misalignment. Technological adaptation faces hurdles through infrastructure limitations, digital literacy gaps, and technology access inequalities,

while policy implementation grapples with regulatory compliance challenges, enforcement mechanisms, and incentive misalignment.

Surrounding these friction points, the diagram presents adaptive strategies that offer potential pathways for resolution. These include collaborative knowledge platforms, flexible policy frameworks, capacity building initiatives, contextual technology design, and participatory decision-making mechanisms. This visual representation is grounded in established theoretical frameworks, including Institutional Theory (North, 1990), the Technology Acceptance Model (Davis, 1989), and Adaptive Governance Frameworks.

The diagram 1 yields several key theoretical insights: friction should be viewed not as a barrier but as a negotiation space, institutional change follows non-linear patterns, and adaptation requires continuous mutual learning. Specifically contextualized within Sri Lankan Agricultural SME settings, the diagram reflects local economic and cultural dynamics. This visualization challenges linear technology adoption models, emphasizes the importance of contextual understanding, and advocates for nuanced policy interventions. Ultimately, the diagram 1 serves as a dynamic model demonstrating that successful carbon neutrality implementation demands a deep understanding of local contexts, flexible policy frameworks, engagement with traditional knowledge systems, and collaborative approaches to technological innovation.

5.7 Theoretical Contributions

This research extends institutional theory by demonstrating how informal institutions - particularly traditional farming practices and cultural norms - interact with formal technological interventions in unexpected ways. While the implementation of IoT-based irrigation systems-powered climate analytics demonstrated a 30% reduction in water and energy waste, these results challenge the technological determinism prevalent in current literature. Mohamed et al.'s (2023) optimistic outlook on digital agriculture in developing nations, we argue, fails to account for what Scott (2014) terms the "institutional pillars" - regulatory, normative, and cultural-cognitive elements that fundamentally shape technology adoption patterns.

The study also advances understanding of the technology acceptance model in developing agricultural contexts. Unlike traditional TAM applications that emphasize perceived usefulness and ease of use, the findings reveal that in Sri Lankan agricultural SMEs, institutional

legitimacy and social capital play equally crucial roles in technology adoption decisions. This extends that Agricultural technology adoption by introducing a new dimension of social-institutional factors that mediate between technological capability and actual usage.

5.8 Institutional Dynamics and Policy Implementation

Through the theoretical lens of institutional entrepreneurship (DiMaggio, 1988), the analysis reveals how the absence of standardized carbon accounting frameworks reflects broader institutional voids in developing economies. These voids, we argue, create a particularly challenging environment for what Maguire et al. (2004) term "institutional work" - the purposive actions aimed at creating, maintaining, and disrupting institutions. The findings challenge Rasul's (2021) optimistic assessment of policy integration by demonstrating how institutional complexity impedes the translation of policy intentions into practical outcomes.

The study contributes to institutional theory by identifying what we term "institutional friction points" - specific areas where formal institutional changes (such as new carbon policies) collide with informal institutional constraints (such as traditional farming practices). This theoretical framework helps explain why seemingly rational policy initiatives often fail to achieve their intended outcomes, extending beyond Naveen et al.'s (2024) more mechanistic analysis of policy implementation.

5.9 Knowledge Integration and Institutional Change

The research makes a novel contribution to knowledge management theory in agricultural contexts by demonstrating the limitations of existing knowledge transfer models. While Ginige et al.'s (2016) integrated knowledge ecosystem model provides a starting point, the findings suggest a more complex institutional ecology where traditional and modern knowledge systems interact through what we term "adaptive knowledge interfaces." This theoretical construct helps explain both the successes and failures observed in SLSEA's partnership model, contributing to the understanding of knowledge transfer in institutionally complex environments.

Drawing on Schaper's (2022) work, we extend institutional theory by demonstrating how capacity-building initiatives must navigate what we term "institutional distance" - the gap between existing institutional arrangements and desired institutional configurations. This theoretical framework helps explain why technical expertise shortages persist despite training initiatives, and why resource allocation patterns often resist change despite clear economic incentives.

5.10 Theoretical Synthesis

By integrating institutional theory with technology acceptance models and knowledge management frameworks, the research provides a more comprehensive theoretical basis for understanding carbon neutrality initiatives in developing agricultural contexts. This theoretical synthesis suggests that successful interventions must address not only technological and economic factors but also the complex institutional ecology in which these initiatives operate.

5.11 Future Research Directions

This study opens several avenues for future research. First, longitudinal studies could examine how adaptive knowledge interfaces evolve over time. Second, comparative analyses across different regions could help identify transferable success factors. Finally, research into innovative financing mechanisms could address the persistent resource constraints identified in this study (International Energy Agency, 2020).

The research demonstrates that successful carbon neutrality initiatives in agricultural SMEs require a delicate balance between technological innovation, institutional support, and cultural sensitivity. As Schaper (2022) suggests, the path forward lies not in wholesale transformation but in thoughtful integration of modern and traditional approaches within appropriate institutional frameworks.

5.12 Key Recommendations for Carbon-Neutral Agricultural SMEs

5.12.1 Carbon-Neutral Practices

1. **Transition to Organic Fertilizers & Renewable Energy:** Prioritize the shift from chemical inputs and diesel-powered machinery to organic fertilizers and renewable sources such as solar irrigation and biogas digesters. This transition can achieve up to 30% reductions in greenhouse gas emissions.
2. **Adopt Standardized Carbon-Accounting Tools & Certifications:** Deploy government-backed carbon accounting platforms and pursue ISO 14064 certification to ensure credible measurement and facilitate access to carbon-conscious markets.
3. **Expand Green-Finance Mechanisms:** Establish concessional loan schemes and SME climate-credit lines to enable investment in low-carbon technologies and practices.

4. **Initiate Agroforestry & Reforestation:** Launch targeted agroforestry and reforestation programs to sequester carbon and improve long-term land sustainability.
5. **Upgrade Cold Storage & Logistics:** Invest in cold storage facilities and optimized logistics networks to reduce food loss and curb methane emissions from spoilage.

5.12.2 Digital & Climate-Smart Technologies

1. **Implement IoT & Climate Analytics:** Deploy IoT-based irrigation systems, soil-moisture sensors, and climate-analytics platforms to enable precise resource management and achieve 30–40% water and energy savings.
2. **Establish Real-Time Climate Monitoring:** Set up climate monitoring stations and decision-support tools to enhance adaptation to extreme weather and inform timely interventions.
3. **Digitize Crop Insurance:** Modernize crop insurance schemes through digital platforms, enabling rapid, transparent payouts and streamlined post-disaster relief.
4. **Develop Drought-Resistant Varieties:** Support genetic mapping and breeding of drought- and climate-resilient crop varieties for enhanced adaptation.

5.12.3 Policy & Institutional Support

1. **Mandate Carbon-Footprint Reporting:** Require annual carbon footprint disclosures for agricultural SMEs, establishing a robust baseline for emission reduction efforts.
2. **Provide Targeted Subsidies & Tax Incentives:** Integrate incentives for low-carbon farming and digital innovation into the Agriculture Modernization Policy (2025–2030).
3. **Launch Green SME Credit Schemes:** Facilitate access to finance for investments in solar, IoT, and sustainable fertilizers through dedicated credit lines and guarantees.
4. **Forge Public-Private Partnerships:** Collaborate with agencies such as the Sri Lanka Sustainable Energy Authority (SLSEA) to scale up renewable energy and IoT-based resilience systems.
5. **Establish Agri-Tech Innovation Grants:** Create grant programs for startups and SMEs integrating AI, blockchain, and IoT into agricultural solutions.

5.12.4 Implementation Roadmap: Prioritization & Feasibility

To turn these recommendations into action, we propose a phased roadmap that balances cost, institutional complexity, and anticipated impact. The following matrix ranks each action cluster by phase and feasibility:

Phase	Recommendation Cluster	Indicative Cost	Institutional Complexity	Expected Impact	Feasibility*
Immediate	Mandatory carbon reporting; govt. carbon tools	Low	Low	Baseline + regulatory signal	High
Immediate	Expand green finance lines (SME loans, credit guarantees)	Low–Medium	Medium	Unlocks capital for low-carbon tech	High
Short-term	IoT irrigation & soil-sensor pilots	Medium	Medium	30–40% resource savings; proof of concept	Medium–High
Short-term	Digital crop insurance & real-time climate advisory	Medium	Medium	Faster disaster recovery, yield stability	Medium–High
Medium-term	Agroforestry & reforestation programs	Medium	High	Long-term carbon sequestration, soil health	Medium
Medium-term	Cold storage & logistics upgrades	High	High	Up to 20% reduction in food-loss methane	Medium
Long-term	Distributed renewables (solar, biogas)	High	High	Up to 30% GHG reduction, rural energy security	Medium
Long-term	Drought-resistant crop varieties at scale	High	High	Enhanced climate resilience, yield gains	Medium–Low

*Feasibility reflects cost, institutional complexity, and current capacity readiness.

Sequencing Logic:

1. Build measurement and finance foundations first (carbon reporting + green credit) to create regulatory incentives and liquidity.
2. Pilot digital solutions in readiness hotspots, refine via adaptive knowledge interfaces, then scale up nationally.
3. Introduce nature-based solutions (agroforestry) once robust monitoring and finance mechanisms are established.
4. Tackle capital-intensive infrastructure after demonstrating early wins and forging key partnerships.

This roadmap is aligned with the milestones of Sri Lanka's Agriculture Modernization Policy and is designed to be iteratively updated through the adaptive knowledge-interface process, ensuring that both traditional expertise and digital innovation are continually integrated.

6.0 Conclusion

This research provides critical insights into the complex challenges and opportunities of implementing carbon neutrality measures in Sri Lankan agricultural SMEs during a period of economic uncertainty. Through a rigorous Delphi study involving 12 experts across key agricultural regions, the research reveals several fundamental findings that challenge existing assumptions about technological adoption and sustainable practices in developing economies.

The study demonstrates that achieving carbon neutrality in Sri Lankan agricultural SMEs requires more than mere technological solutions. While digital innovations show promise - with IoT-based irrigation systems reducing water and energy waste by 30% - successful implementation demands a delicate balance between modern technology and traditional agricultural practices. The institutional friction points framework developed through this research reveals how formal policy initiatives often collide with informal institutional constraints, creating implementation barriers that cannot be resolved through technology alone.

A key theoretical contribution emerges from the identification of "adaptive knowledge interfaces" - points where traditional farming knowledge and modern technological solutions must find common ground. This concept helps explain why some carbon neutrality initiatives succeed while others fail, even within similar contexts. The research challenges the

technological determinism prevalent in existing literature, showing that successful adoption depends heavily on institutional legitimacy and social capital.

The practical implications of this research are significant for policymakers and practitioners. As Sri Lanka updates its Agriculture Modernization Policy (2025-2030), our findings suggest that effective carbon neutrality initiatives must:

- Integrate traditional agricultural knowledge with modern technological solutions
- Address institutional barriers through targeted policy interventions
- Develop flexible financing mechanisms that account for SME resource constraints
- Create supportive frameworks for knowledge transfer and capacity building

Looking ahead, this research opens new avenues for understanding how developing economies can achieve carbon neutrality while maintaining economic viability. Future research should examine how the institutional friction points framework applies in other developing contexts and investigate the long-term effectiveness of adaptive knowledge interfaces in facilitating sustainable agricultural practices.

Ultimately, this study demonstrates that the path to carbon neutrality in developing agricultural economies requires a nuanced understanding of local contexts, institutional dynamics, and the complex interplay between traditional practices and modern innovations. Success depends not just on technological capability, but on our ability to create inclusive, adaptive frameworks that respect and integrate local knowledge while advancing sustainable agricultural practices.

7.0 References

Asian Development Bank. (2020). *Asia Small and Medium-sized Enterprise Monitor 2020: Volume I – Country and Regional Reviews*. Asian Development Bank.

Bocken, N. M. P., Short, S. W., Rana, P., & Evans, S. (2014). *A literature and practice review to develop sustainable business model archetypes*. *Journal of Cleaner Production*, 65, 42-56.

CSR Asia. (2011). *Climate Change Adaptation: Engaging business in Asia*. Retrieved from <http://sa.indiaenvironmentportal.org.in/files/climate%20change%20adaptation%20in%20asia.pdf>

Davis, F. D. (1989). *Perceived usefulness, perceived ease of use, and user acceptance of information technology*. *MIS Quarterly*, 13(3), 319-340.

DiMaggio, P. J. (1988). *Interest and agency in institutional theory*. In L. Zucker (Ed.), *Institutional patterns and organizations: Culture and environment* (pp. 3-21). Cambridge: Ballinger.

Dilrukshi, R., Hettiarachchi, M., & Sivagnanasundaram, J. (2021). *Precision Agricultural Technologies for enhancing crop productivity: A way forward to Sri Lankan Agriculture*. Sri Lankan Journal of Food and Agriculture, 12(2), 98-105.

Esham, M., & Garforth, C. (2013). *Agricultural sustainability and knowledge transfer in developing economies*. International Journal of Agricultural Sustainability, 11(3), 263-275.

European Commission. (2021). *The European Green Deal: Sustainable growth strategies and policy frameworks*. European Commission Publications.

Ginige, A., & Sivagnanasundaram, J. (2019). *Enhancing agricultural sustainability through crowdsensing: A smart computing approach*. The 11th International Conference on Agricultural Technologies, 45-62.

Ginige, A., Walisadeera, A. I., & Ginige, T. (2016). *Digital knowledge ecosystem for achieving sustainable agriculture production: A case study from Sri Lanka*. IEEE Conference on Data Mining, 234-248.

International Energy Agency. (2020). *Energy efficiency 2020: The critical role of SMEs in energy transition*. International Energy Agency.

Maguire, S., Hardy, C., & Lawrence, T. B. (2004). *Institutional entrepreneurship in emerging fields: HIV/AIDS treatment advocacy in Canada*. Academy of Management Journal, 47(5), 657-679.

Mohamed, M. S. A., Wathugala, D. L., & Indika, W. A. (2023). *Decision Support System Enabled Digital Mobile Platform to Assist Farmers Towards Agricultural Production Sustainability in Sri Lanka*. Tropical Agricultural Research and Extension, 26(1), 1-15.

Naveen, N., Datta, P., Behera, B., & Rahut, D. B. (2024). *Climate-smart agriculture in South Asia: Exploring practices, determinants, and contribution to sustainable development goals*. Mitigation and Adaptation Strategies for Global Change. <https://doi.org/10.1007/s11027-024-10126-4>

North, D. C. (1990). *Institutions, institutional change, and economic performance*. Cambridge University Press.

OECD. (2018). *Greening SMEs for sustainable development: Policy guidance and best practices*. Organisation for Economic Co-operation and Development.

Rasul, G. (2021). *A framework for addressing the twin challenges of COVID-19 and climate change for sustainable agriculture and food security in South Asia*. Frontiers in Sustainable Food Systems, 5, 679037.

Schaper, M. (2022). *SME responses to climate change in Southeast Asia*. Cambridge University Press.

Scott, W. R. (2014). *Institutions and organizations: Ideas, interests, and identities*. Sage Publications.

Tam, S. (2019). *Sounding the alarm: Is the Sri Lankan tourism sector prepared for climate change?* University of Waterloo.

Udayanga, L., & Najim, M. M. M. (2024). *Climate change impacts on agricultural sector in Sri Lanka: Necessity of precision agricultural technologies*. In *Climate-smart and resilient food systems and sustainability* (pp. 356-372). Springer.

Walker, H., Di Sisto, L., & McBain, D. (2008). *Drivers and barriers to environmental supply chain management practices: Lessons from the public and private sectors*. *Journal of Purchasing and Supply Management*, 14(1), 69-85.

Walisadeera, A. I., & Ginige, A. (2024). *IoT-based irrigation systems for sustainable agriculture: Case studies from Sri Lanka*. *Journal of Agricultural Informatics*, 15(4), 345-362.

Williamson, O. E. (1985). *The economic institutions of capitalism: Firms, markets, relational contracting*. Free Press.