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Agricultural Green Innovation and Food Security in Indonesia: Exploring Green Economy Transformation

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ABSTRACT

Sustainable development in developing countries requires integrated approaches addressing environmental sustainability, economic growth, and food security simultaneously. This study advances agricultural innovation research by employing structural equation modeling to examine the mediating role of green economy transformation in the relationship between individual farmer innovations and sustainable food security outcomes, providing novel empirical evidence on systemic mechanisms that translate micro-level innovations into macro–level food security benefits in developing country contexts. A cross–sectional survey of 398 Indonesian smallholder farmers employed Partial Least Squares Structural Equation Modeling to test complex mediation relationships within an integrated theoretical framework. Green entrepreneurial innovation was measured through product, process, organizational, and marketing dimensions, while green economy transformation encompassed resource efficiency, technology access, policy support, and environmental contribution. Results explained 61.2% of food security variance with all relationships statistically significant ($p < 0.001$). Green entrepreneurial innovation influenced food security directly ($\beta = 0.394$) and through green economy transformation ($\beta = 0.668 \rightarrow 0.421$). Mediation analysis revealed partial mediation, with green economy transformation accounting for 41.6% of the total effect ($\beta = 0.281$). Findings demonstrate that sustainable food security requires integrated approaches targeting both individual farmer capacity and broader green economy development. Policy interventions addressing innovations alone

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achieve suboptimal results without complementary systemic changes in markets, institutions, and infrastructure, providing valuable guidance for evidence–based sustainable agricultural development policy across developing countries.

Keywords: Green Entrepreneurship; Sustainable Food Security; Green Economy Transformation; Smallholder Farmers; Agricultural Innovation; Indonesia

1. Introduction

The pursuit of sustainable development has emerged as one of the most critical challenges facing humanity in the 21st century, requiring integrated approaches that simultaneously address environmental sustainability, economic growth, and social well–being. The Sustainable Development Goals (SDGs), adopted by all United Nations Member States in 2015 as part of the 2030 Agenda for Sustainable Development, recognize that achieving sustainable development requires universal action by all countries to promote prosperity while protecting the planet, acknowledging that ending poverty must go hand–in–hand with strategies that build economic growth and address social needs while tackling climate change and environmental protection. Research increasingly recognizes corporate social responsibility as an important factor for fostering sustainable development and enhancing social welfare [1] The SDGs target all three dimensions of sustainability—environmental, economic, and social—emphasizing that these goals are integrated and interconnected, requiring that action in one area affects outcomes in others.

Developing countries face particularly acute challenges in balancing economic development imperatives with environmental sustainability objectives, often characterized by resource constraints, institutional limitations, and competing developmental priorities. Cross–country comparisons reveal that countries with lower institutional quality present significant challenges in environmental efficiency, where weaker institutional frameworks, including corruption and ineffective governance, hamper the enforcement of environmental regulations and incentives for adopting eco–friendly technologies [2]. Environmental performance varies significantly across countries due to diverse institutional factors, with metafrontier analysis demonstrating that economic policy uncertainty, institutional quality, and political orientation significantly affect national environmental outcomes [3]. The impact of economic policy uncertainty on environmental efficiency is particularly pronounced in developing countries, where institutional quality and political orientation play crucial moderating roles in determining environmental policy effectiveness [4]. For developing countries, sustainable consumption and production can offer opportunities such as the creation of new markets, green jobs, and more efficient natural resource management, providing potential pathways to transition to more resource efficient, environmentally sound and competitive technologies.

Food security challenges remain a persistent global issue, with sustainable food security evolving beyond traditional measures to encompass environmental sustainability and resilience dimensions [5, 6]. Food security represents a critical intersection between environmental sustainability and human development, encompassing not only immediate nutritional needs but also long–term agricultural system resilience and environmental stewardship. The SDGs include targets to end all forms of hunger and malnutrition by 2030, ensuring all people have sufficient and nutritious food while promoting sustainable agriculture, supporting small–scale farmers, and ensuring equal access to land, technology, and markets. This expanded framework requires approaches that address immediate nutritional needs alongside environmental sustainability, climate resilience, and economic viability for smallholder farmers who constitute a significant portion of agricultural producers in developing countries. Climate change and resource degradation create mounting pressures on agricultural systems, while growing populations simultaneously demand increased food production through more sustainable methods. This challenge is particularly acute in developing countries where smallholder farm-

ers constitute the majority of agricultural producers while facing mounting pressures from climate change, resource degradation, and market access constraints that threaten both immediate food security and long–term agricultural sustainability.

Green entrepreneurship encompasses the adoption of environmentally friendly practices, technologies, and business approaches that simultaneously pursue economic returns and environmental benefits. Digital technologies are increasingly recognized as enablers of sustainable agricultural transformation in developing countries, with studies demonstrating that digital solutions can transform smallholder agriculture through improved access to information, financial services, and market linkages[7, 8]. The concept of green economy transformation—characterized by increased resource efficiency, enhanced access to sustainable technologies, supportive policy frameworks, and strengthened environmental stewardship—represents a systemic approach to agricultural development[9, 10]. Recent advances in behavioral intervention research reveal that nudging techniques can effectively promote the adoption of sustainable practices, with studies demonstrating that gender, education, and psychological factors such as environmental responsibility significantly impact sustainable behaviors among consumers[11]. However, the adoption and scaling of green innovations in developing country agricultural contexts remain challenging due to resource constraints, institutional barriers, and limited access to supportive infrastructure and services.

Research on green economic growth, renewable energy and food security in Sub–Saharan Africa demonstrates that green economy initiatives can positively impact food security, though effects vary across different components and contexts[12]. Studies suggest that achieving sustainable food security requires not only encouraging farmer–level adoption of green practices but also fostering broader economic changes that support and reward sustainable agriculture. However, systematic evidence on how individual innovations translate into broader economic transformation remains limited, particularly regarding the mediating mechanisms involved. Recent research demonstrates that individual farmer innovations translate into broader system–level outcomes through multiple mediation mechanisms, with multilevel innovation platforms serving as crucial intermediaries facilitating the scaling of individual innovations to systemic change[13, 14]. Climate policy navigation reveals the complex influence of lobbying trends and narratives in shaping environmental governance frameworks, highlighting the importance of understanding policy mechanisms that support sustainability transitions[15]. Bibliometric analysis of transformative innovation policies and sustainable development goals demonstrates the nexus between policy innovation and sustainability outcomes, though systematic evidence on agricultural contexts remains limited[16]. Most existing studies examine green innovations and food security as separate phenomena, with limited research investigating their causal relationships and underlying mechanisms. The concept of green economy transformation represents a potential mediating mechanism through which individual innovations may generate broader systemic impacts, but systematic evidence on these mediation relationships remains limited, particularly regarding how green economy transformation processes occur at local levels and influence food security outcomes among smallholder farmers in developing countries. Given these empirical and theoretical gaps, there is an urgent need for robust evidence from developing country contexts where green economy transformation is actively being pursued.

This study advances agricultural innovation research by employing structural equation modeling to examine the mediating role of green economy transformation in the relationship between green entrepreneurial innovation and sustainable food security among Indonesian smallholder farmers. Indonesia provides an ideal setting for examining these relationships, given its status as a major developing country with significant agricultural diversity and ongoing policy commitments to both food security and environmental sustainability. The country's land reform initiatives, while aimed at improving agricultural livelihoods, present complex challenges for climate commitments and sustainable development[17]. Quantitative studies employing robust methodological approaches such as structural equation modeling remain scarce in developing country agricultural contexts, limiting evidence–based policy formu-

lation. To understand how national green economy initiatives translate into local–level impacts and guide evidence–based policy implementation, empirical research in representative agricultural contexts is essential. This study was conducted in Deli Serdang Regency, North Sumatera Province, Indonesia, which provides an ideal context for examining green entrepreneurship and food security relationships among smallholder farmers. The regency's diverse agricultural systems, ongoing sustainability initiatives, and representative characteristics of Southeast Asian smallholder farming make it particularly suitable for testing the generalizability of relationships between green innovation and food security that may apply to similar contexts across Indonesia and the broader developing world.

Against this background, this study addresses four fundamental research questions:

(RQ1) Does green entrepreneurial innovation directly influence sustainable food security among smallholder farmers?

(RQ2) How does green entrepreneurial innovation affect green economy transformation at the local level?

(RQ3) What is the relationship between green economy transformation and sustainable food security outcomes?

(RQ4) Does green economy transformation mediate the relationship between green entrepreneurial innovation and sustainable food security?

This research contributes to the literature by providing empirical evidence on these relationships within developing country contexts, with implications for sustainable agricultural development policy and practice.

2. Literature Review

2.1. Sustainable Food Security in Developing Countries

Food security remains a critical global challenge, particularly in developing countries where agricultural systems face multiple pressures from climate change, population growth, and resource constraints. The concept of sustainable food security has evolved beyond traditional measures of availability, access, utilization, and stability to encompass environmental sustainability and resilience [5, 6]. This multi–dimensional approach recognizes that food security interventions must simultaneously address nutritional outcomes, environmental protection, and economic viability to be truly sustainable.

Recent advances in food security measurement have moved beyond the traditional four pillars to incorporate sustainability and resilience dimensions, with multi–dimensional frameworks recognizing that sustainable food security requires assessment of environmental, economic, social, and resilience domains simultaneously [18]. Validated instruments including household dietary diversity, food access scales, and sustainability indicators have been developed and tested in developing country contexts, with composite measure approaches showing particular promise [19].

New measures have been developed to assess the "other" three pillars of food security—availability, utilization, and stability—beyond the commonly measured access dimension, providing more comprehensive assessment tools for researchers and practitioners [20]. Research on ranking food security indicators and metrics using Delphi approaches provides insights into expert consensus on appropriate measurement frameworks for different contexts [21].

Research from Vietnam demonstrates that factors affecting the adoption of sustainable agricultural practices include institutional support, environmental awareness, and economic incentives, with panel data analysis revealing the importance of integrated policy approaches [22]. Similar patterns have been observed across developing countries, where social norms and innovation adoption in rural communities play crucial roles in determining food security outcomes [23].

Studies on digitalization for sustainable agri–food systems reveal both potential and risks for enhancing food security, with regional analysis showing that digital solutions can improve supply chain performance and optimize natural resource use, though adoption remains at early stages in many developing regions [24]. Research on barriers and enablers of digital technologies for sustainable agricultural development demonstrates the impor-

tance of addressing technological, economic, and social constraints simultaneously [25].

2.2. Green Entrepreneurial Innovation in Agriculture

Green entrepreneurship has emerged as a powerful mechanism for driving sustainable transformation in agricultural systems, particularly among smallholder farmers [26]. Recent studies indicate that green entrepreneurial activities encompass not only the adoption of environmentally friendly practices but also the development of innovative business models that create value from sustainability [27]. In the agricultural context, green entrepreneurs are characterized by their proactive approach to environmental challenges, developing solutions that simultaneously improve productivity and reduce environmental impact.

Recent empirical studies have examined the relationship between agricultural green innovation and food security outcomes in developing countries, utilizing structural equation modeling or mediation analysis. Research in Ghana investigated the effect of food security awareness, innovation characteristics, and agricultural experience on the behavioral intention to adopt digital innovation in agriculture using partial least squares structural equation modeling, finding that personal innovativeness significantly affects food security awareness and innovation adoption intentions [28]. In Tanzania, studies examined the mediating effects of green innovation on the relationship between green absorptive capacity and agripreneurs' intention to adopt precision agriculture, finding that green innovation significantly mediates the relationship between green absorptive capacity and adoption intentions [29].

The literature reveals significant variation in the adoption and impact of green entrepreneurial innovations. Environmental impacts in integrated production systems demonstrate the potential for sustainable approaches to simultaneously address productivity and environmental objectives [30]. Digital technology and services for sustainable agriculture show promise for enhancing farmer capabilities, though comprehensive service provision throughout the farming cycle remains challenging, particularly for smallholder farmers [8].

Research on green entrepreneurship among students reveals that entrepreneurial education and green knowledge positively influence interest in green entrepreneurship, suggesting the importance of education and awareness–building for fostering green entrepreneurial behavior [27]. The identification of relationships among indicators of sustainable entrepreneurial ecosystems in agricultural startups provides frameworks for understanding the factors that support green entrepreneurship development [26].

2.3. Green Economy Transformation and Agricultural Development

The green economy paradigm offers a framework for understanding how environmental sustainability can be integrated with economic development objectives [31]. In agricultural contexts, green economy principles emphasize resource efficiency, waste reduction, and the creation of sustainable value chains that benefit both producers and consumers. Recent empirical evidence suggests that countries with stronger green economy policies demonstrate better performance in agricultural sustainability indicators, though the relationship varies significantly across different contexts.

Research on green finance, land transfer and agricultural green total factor productivity in China demonstrates that green finance significantly enhances agricultural productivity by increasing land transfer and stimulating rural entrepreneurial vitality, with impacts varying across regions and regulatory environments [10]. Analysis of sustainable energy and environmental policies in agriculture within the EU regarding the European Green Deal provides insights into policy frameworks for supporting sustainability objectives [32]. Studies on cultivated land utilization green transformation show positive impacts on agricultural economic growth, advocating for policies that support functional and pattern transformation [33].

Research on how farmers' green production behavior can be promoted provides comprehensive literature review of drivers and incentives for behavioral change, emphasizing the need for multi–agent incentive mechanism systems involving government, market, and social participation [9]. Regional evidence from ASEAN economies shows that green investments and economic

growth significantly contribute to sustainable development goals, though the effectiveness varies across countries and sectors [34].

Econometric insights into inclusive green growth, technological innovation and financial development dynamics in Asia reveal that financial development significantly promotes green growth, while technological innovation impacts vary across regions, suggesting the need for tailored approaches to green economy development [31]. However, a critical gap exists in understanding how green economy transformation occurs at the farm level and how it mediates the relationship between individual innovations and broader food security outcomes.

2.4. Mediation Mechanisms in Agricultural Innovation Systems

Recent research demonstrates that individual farmer innovations translate into broader system–level outcomes through multiple mediation mechanisms. Previous research found that multilevel innovation platforms serve as crucial intermediaries, facilitating the scaling of individual innovations to systemic change [13]. Similarly, subsequent studies demonstrated how social–ecological systems frameworks help explain the mechanisms through which individual farmer actions promote collective outcomes [14]. These studies demonstrate that direct effects alone are insufficient, with intermediate mechanisms playing crucial roles in translating individual innovations into broader impacts.

Multi–stakeholder platforms have proven effective in enhancing collaboration, knowledge exchange, and influence mediation among farmers, researchers, and other stakeholders, contributing to enhanced capacity to innovate and scaling of innovations [35]. Innovation platforms facilitate collective action and foster innovation by providing social space and facilitating interactions among farmers, researchers, and other stakeholders, though sustained innovation requires addressing complex value chain issues and integrating relevant actors across levels.

The Science and Technology Backyard model in rural China demonstrates how innovation intermediaries can evolve from knowledge brokers to systemic innovation facilitators, though broader collaboration mechanisms are needed for scaling beyond individual communities [36]. Understanding innovation platform effectiveness through experiences from West and Central Africa reveals the importance of context–specific approaches and adaptive management in facilitating agricultural innovation [37].

The mediation role of green economy transformation is supported by empirical evidence showing how intermediate mechanisms translate individual innovations into broader outcomes. These studies demonstrate that innovation platforms and intermediary mechanisms partially mediate individual–to–system relationships, while direct effects remain important, providing a theoretical foundation for understanding how green economy transformation mediates innovation–food security relationships.

2.5. Research Gaps and Conceptual Framework

Despite growing interest in sustainable agriculture, several empirical gaps limit our understanding of the innovation–food security nexus. First, most studies examine green innovations and food security as separate phenomena, with limited research investigating their causal relationships. Second, the majority of quantitative studies focus on developed countries or single–country contexts, limiting generalizability to diverse developing country settings. Third, while the green economy concept is increasingly prominent in policy discourse, empirical measurement and testing of its mediating role in agricultural systems remains nascent.

Theoretically, the literature lacks integrated frameworks that connect micro–level entrepreneurial innovations with macro–level economic transformation and food security outcomes. Recent research demonstrates the effectiveness of combining Resource–Based View and Institutional Theory to understand agricultural innovation systems in emerging economies [38], while the shift toward Sustainable Innovation 2.0 emphasizes socio–ecological well–being over purely financial outcomes [39]. The integration of multiple theoretical perspectives in agricultural innovation research has proven effective, with social theory integration enhancing social transformation in agricultural research for development [40].

A multidisciplinary approach to assess smallholder farmers' adoption of new technologies in development interventions reveals the complexity of factors influencing adoption, including barriers related to agricultural production systems, livelihoods, and power relationships [41]. Methodologically, few studies employ robust techniques to examine mediation relationships in agricultural contexts. While structural equation modeling has been used to examine innovation adoption, its application to understanding complex relationships between green entrepreneurship, economic transformation, and food security outcomes remains limited.

2.6. Conceptual Framework and Hypotheses Development

Based on the literature review, this study proposes a conceptual framework integrating Resource–Based View theory (for understanding green entrepreneurial capabilities), Institutional Theory (for green economy transformation), and Sustainable Livelihood Framework (for food security outcomes). Following the approach proposed in recent research, this study integrates Resource–Based View theory for understanding green entrepreneurial capabilities[, Institutional Theory for green economy transformation, and Sustainable Livelihood Framework for food security outcomes. The framework posits that:

H1. *Green entrepreneurial innovation positively influences sustainable food security among smallholder farmers.*

H2. *Green economy transformation positively influences sustainable food security outcomes.*

H3. *Green entrepreneurial innovation positively influences green economy transformation at the local level.*

H4. *Green economy transformation mediates the relationship between green entrepreneurial innovation and sustainable food security.*

3. Methodology

3.1. Research Design and Approach

This study employs a quantitative research design utilizing a cross–sectional survey approach to examine the complex relationships between green entrepreneurial innovation, green economy transformation, and sustainable food security among smallholder farmers. The research adopts a positivist philosophical stance, applying structural equation modeling to test hypothesized relationships and mediation effects within an integrated theoretical framework.

Data analysis employs Partial Least Squares Structural Equation Modeling (PLS–SEM) following established best practices for reporting and interpretation [42]. This approach was chosen for its robustness with complex mediation models and suitability for exploratory research with cross–sectional data. The analytical process incorporates advanced prediction metrics including PLSpredict to evaluate model predictive relevance beyond traditional fit indices [43].

The research process followed a systematic five–phase approach designed to ensure methodological rigor and data quality. **Figure 1** presents the detailed research phases implemented throughout the study.

3.2. Study Context and Setting

The research was conducted in Deli Serdang Regency, North Sumatera Province, Indonesia, encompassing 2,497.72 km^2 with agriculture serving as the primary economic sector supporting over 400,000 farming households across diverse agro–ecological zones. The regency demonstrates significant agricultural diversity with active production across multiple sectors: food crops (particularly rice and maize), horticulture (fruits and vegetables), plantation agriculture (oil palm and rubber), and integrated crop–livestock systems.

This agricultural diversity provides natural variation in farming practices and green innovation adoption that is essential for examining the relationships of interest while maintaining sufficient sample sizes across different agricultural subsectors. The region faces typical challenges confronting developing country agriculture, including climate variability, market access constraints, limited access to modern technologies, and resource limitations, making it representative of contexts where green entrepreneurship policies are being implemented.

The regency's positioning within Indonesia's broader green economy transformation framework,

combined with ongoing implementation of sustainable agriculture initiatives through government and NGO programs, provides natural variation in green economy participation among farmers. This policy environment creates an ideal natural experiment for examining how individual farmer innovations contribute to broader green economy transformation while generating food security benefits.

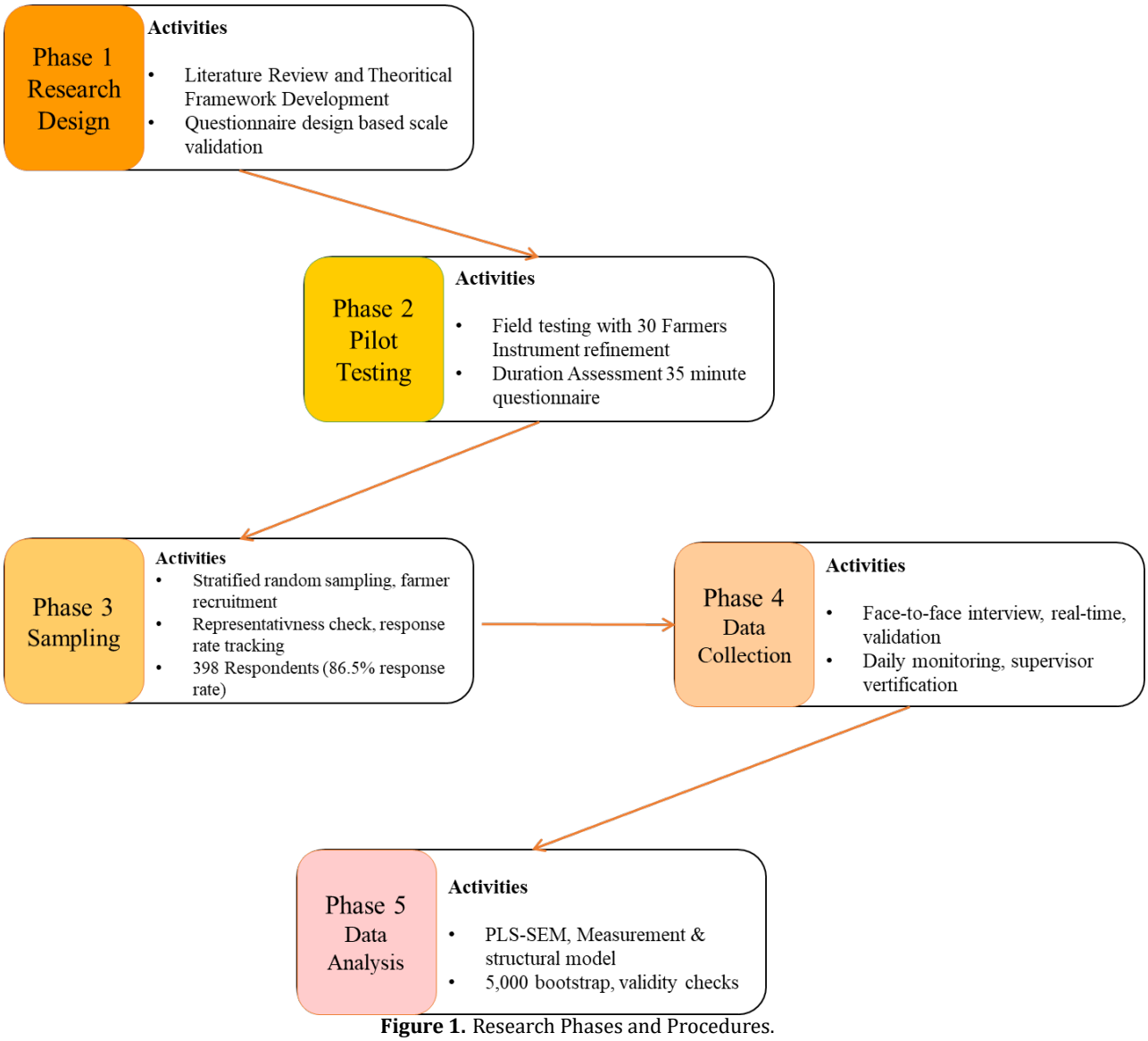

Figure 1. Research Phases and Procedures.

3.3. Population and Sampling Framework

The target population consists of individual smallholder farmers engaged in various agricultural subsectors within Deli Serdang Regency. The study focuses specifically on Individual Agricultural Holdings, targeting economically active farmers aged 25–60 years who serve as primary decision–makers in their agricultural operations and have maintained active farming engagement for a minimum of two years.

A probability sampling approach utilizing stratified random sampling was implemented to ensure representativeness across different agricultural sectors and farm sizes. The stratification variables included primary agricultural activity encompassing food crops, horticulture, plantation systems, and mixed farming operations, as well as farm size categories to ensure adequate representation across the diversity of smallholder farming

systems within the study region. This stratification approach enabled the examination of relationships across different agricultural contexts while maintaining statistical power for the intended analyses.

Sample size determination followed established guidelines for PLS–SEM analysis, with statistical power analysis targeting power of 0.80, alpha level of 0.05, and medium effect size ($f^2 = 0.15$). This indicated a minimum required sample of 395 respondents. The target was set at 460 farmers to account for potential non–response, ultimately achieving 398 respondents with an 86.5% response rate that provided adequate statistical power for the structural equation modeling analyses.

3.4. Measurement Instrument and Scales

A structured questionnaire was developed incorporating validated scales from established agricultural innovation and food security literature. The instrument prioritized theoretical grounding and methodological rigor required for structural equation modeling. All constructs utilize 7–point Likert scales anchored by "strongly disagree" to "strongly agree", providing adequate variance for sophisticated statistical analysis. A pilot study involving 30 farmers was conducted in February 2025 to refine instrument clarity and identify potential comprehension issues.

The sustainable food security construct followed established approaches for multi–dimensional food security measurement, incorporating traditional dimensions alongside sustainability and resilience components[6, 19]. Food security assessment in the light of sustainable development goals demonstrates the importance of incorporating economic, environmental, social, and resilience domains simultaneously[5]. The sustainable food security construct was operationalized using a comprehensive framework encompassing four theoretically grounded dimensions derived from established food security literature and adapted for smallholder contexts. Food availability was measured through assessment of harvest adequacy for household food requirements. Food access incorporated both market accessibility for selling agricultural products and ease of purchasing complementary food items from local sources. Food stability focused on the price stability of agricultural outputs over recent months. Food sustainability captured long–term farming operation viability and reduced dependency on external support systems.

Green entrepreneurial innovation was conceptualized through four theoretically grounded dimensions based on established green innovation literature, drawing from validated scales for green entrepreneurship and sustainable entrepreneurship ecosystems[26, 27]. Green product innovation measured the adoption of environmentally friendly materials such as organic fertilizers and sustainable crop varieties. Green process innovation assessed waste management practices and chemical input reduction efforts. Green organizational innovation captured participation in sustainability training programs and implementation of environmental standard operating procedures. Green marketing innovation evaluated environmental benefit promotion activities and interest in certification programs.

Green economy transformation was operationalized to capture local–level participation in green economic activities through four key dimensions, following frameworks for measuring food system sustainability with multi–dimensional perspectives[18]. Resource efficiency measures water and energy conservation techniques along with land optimization practices that reflect core green economy principles. Technology access assessed both modern agricultural equipment usage and access to green technology information through extension services and media channels. Policy support captured participation in government sustainability programs, reflecting the institutional dimension of green economy transformation. Environmental contribution measured environmental protection behaviors that demonstrate farmer commitment to sustainable practices beyond immediate economic benefits.

Scale validation employed item response theory and composite measure approaches consistent with recent food security measurement advances[19]. The integration of sustainability dimensions followed frameworks demonstrated in developing country contexts, with validation procedures including exploratory factor analysis, reliability testing using Cronbach's Alpha, and multiple validity assessments following established procedures for agricultural research contexts.

3.5. Data Collection Procedures and Quality Control

Data collection was implemented through face–to–face interviews conducted by trained enumerators fluent in local languages during March to May 2025. This approach was selected to ensure high response rates in rural contexts, provide clarification of technical terms for farmers with varying education levels, and maintain data quality through direct supervision and real–time validation. Interview duration averaged 35 minutes, confirming feasibility for farmer participation without excessive time burden.

All participants provided written informed consent following a comprehensive explanation of research purposes, data usage protocols, confidentiality protections, and their rights as research participants. The informed consent process was conducted in participants' preferred language (Bahasa Indonesia) and included explicit statements regarding voluntary participation with rights to withdraw at any stage without penalty, confidentiality and anonymization procedures for data protection.

3.6. Analytical Strategy

The analytical process follows a systematic two–stage approach consistent with established best practices for PLS–SEM analysis [42]. The measurement model assessment evaluates the quality of indicators through convergent validity (factor loadings > 0.70, AVE > 0.50), internal consistency reliability (Cronbach's Alpha and Composite Reliability > 0.70), and discriminant validity (Fornell–Larcker criterion and HTMT ratios < 0.85). Following successful measurement model validation, the structural model assessment examines relationships between latent constructs, with collinearity assessment (VIF < 5.0), path coefficient significance through bootstrapping procedures (5,000 subsamples), and model explanatory power evaluation (R^2 and Q^2 values).

Mediation analysis represents a critical component of the analytical strategy, examining whether green economy transformation mediates the relationship between green entrepreneurial innovation and sustainable food security. The analysis employs the specific indirect effects approach with bootstrapping confidence intervals to test mediation hypotheses, following established practices in agricultural innovation research where indirect effects through system–level mechanisms have proven significant [13, 14]. Model validation incorporated bootstrapping procedures with 5,000 iterations and advanced validation techniques to complement PLS–SEM results [44]. Significant mediation is established when the indirect effect demonstrates statistical significance and the bias–corrected confidence interval excludes zero, providing robust evidence for the theorized mediating role of green economy transformation.

3.7. Methodological Strengths and Research Potential

The research design demonstrates several methodological strengths that enhance the reliability and validity of findings. The integration of Resource–Based View theory, Institutional Theory, and Sustainable Livelihood Framework provides a comprehensive theoretical foundation that captures multiple dimensions of the innovation–food security relationship. The PLS–SEM analytical approach is particularly appropriate for examining complex mediation models involving multiple constructs and relationships, while the cross–sectional design enables efficient examination of relationships across a large sample of farmers.

The stratified random sampling approach ensures adequate representation across diverse agricultural systems and farm sizes, enhancing the generalizability of findings within the study region. The use of validated measurement scales adapted for the Indonesian context, combined with rigorous pilot testing procedures, strengthens the quality of data collection instruments. The achieved sample size of 398 respondents provides adequate statistical power for detecting medium effect sizes in structural equation modeling, supporting robust statistical conclusions.

The research contributes significant potential for advancing understanding of sustainable agriculture and food security relationships in developing country contexts. This represents the first comprehensive examination of green economy transformation as a mediating mechanism in Indonesian agriculture, providing novel

empirical evidence for policy development. The methodological approach demonstrates innovation in applying advanced PLS–SEM techniques to agricultural development research, while the theoretical integration offers a framework that can be adapted and tested in other developing country contexts.

The findings have direct policy relevance for sustainable agriculture initiatives, offering evidence–based guidance for designing interventions that effectively link individual farmer innovations with broader economic transformation and food security outcomes. The research framework is scalable and can be replicated across different agricultural regions and developing country contexts, supporting comparative studies and policy learning across different institutional and environmental settings.

3.8. Methodological Limitations and Considerations

Several methodological limitations must be acknowledged that provide important context for interpreting findings and suggest directions for future research. The cross–sectional design, while appropriate for examining relationships at a specific point in time, cannot establish definitive causality between constructs. The theoretical grounding provides strong support for the proposed causal relationships, but longitudinal research would strengthen causal inference and enable examination of dynamic relationships over time.

The reliance on self–reported data introduces potential response bias and social desirability effects, particularly regarding sensitive topics such as environmental practices and income measures. The study employed anonymous data collection procedures and included validation questions to minimize these effects, but objective measures of agricultural practices and outcomes would strengthen future research. The regional focus on Deli Serdang Regency provides valuable context–specific insights but may limit generalizability to other Indonesian regions or developing country contexts with different agro–ecological, economic, or institutional characteristics.

The focus on smallholder farmers, while appropriate for the research objectives, may limit applicability to larger agricultural operations or different farming system contexts. The cultural and institutional context of Indonesia may influence the relationships observed, suggesting the need for comparative research across different developing country settings to assess the broader applicability of findings.

Common method bias represents a potential concern given the single–source nature of data collection, though the study employed multiple validation procedures and the complexity of the structural model reduces the likelihood that relationships are solely attributable to method effects. The analytical approach using PLS–SEM is robust to non–normality and suitable for exploratory research, but confirmatory factor analysis using covariance–based structural equation modeling could provide additional validation of the measurement model in future research.

These limitations provide important considerations for interpreting results while highlighting opportunities for extending the research through longitudinal designs, multi–country comparative studies, and integration of objective measurement approaches. The methodological transparency regarding these limitations enhances the scientific contribution by enabling informed evaluation of findings and supporting replication efforts in different contexts.

4. Results

4.1. Respondent Characteristics and Descriptive Statistics

The final sample comprised 398 smallholder farmers across Deli Serdang Regency, representing diverse agricultural operations and demographic characteristics typical of Indonesian smallholder agriculture. Respondent ages ranged from 25 to 60 years with a mean of 42.3 years (SD = 8.7), indicating a predominantly middle–aged farming population. Male farmers comprised 64.8% of the sample (n = 258), while female farmers represented 35.2% (n = 140), reflecting typical gender participation patterns in Indonesian agriculture.

Educational attainment varied considerably, with the majority completing primary or junior secondary ed-

ucation. Farming experience averaged 16.8 years (SD = 9.2), demonstrating substantial agricultural knowledge within the sample. Farm sizes averaged 1.8 hectares (SD = 1.2), with 78.4% of operations falling below 2 hectares, confirming the predominant smallholder character of the sample. Agricultural activities were diverse, encompassing food crop production, horticulture, plantation crops, and mixed farming systems.

Descriptive statistics revealed interesting patterns in green innovation adoption and food security outcomes. Green entrepreneurial innovation averaged 4.58 on the 7–point scale (SD = 1.28), indicating moderate adoption levels with substantial variation across farmers. Green economy transformation demonstrated a slightly lower mean of 4.23 (SD = 1.41), suggesting that while individual innovations are being adopted, broader economic transformation remains more challenging. Sustainable food security achieved a mean score of 4.76 (SD = 1.19), reflecting generally positive but variable food security outcomes among respondents.

The correlation matrix reveals significant positive relationships between all main constructs, providing initial support for the hypothesized relationships (see **Table 1**). The strongest correlation occurred between green entrepreneurial innovation and green economy transformation (r = 0.587, $p < 0.001$), while moderate correlations were observed between green entrepreneurial innovation and sustainable food security (r = 0.524, $p < 0.001$) and between green economy transformation and sustainable food security (r = 0.568, $p < 0.001$).

Table 1. Descriptive Statistics and Correlation Matrix.

Variable	Mean	SD	1	2	3
1. Green Entrepreneurial Innovation	4.58	1.28	1		
2. Green Economy Transformation	4.23	1.41	0.587***	1	
3. Sustainable Food Security	4.76	1.19	0.524***	0.568***	1

*Note: N = 398. ***$p < 0.001$

4.2. Measurement Model Assessment

The measurement model evaluation demonstrated satisfactory psychometric properties across all constructs, meeting established criteria for convergent validity, internal consistency reliability, and discriminant validity. Factor loadings for all indicators exceeded the recommended threshold of 0.70, ranging from 0.724 to 0.829, indicating strong relationships between observed variables and their respective latent constructs. Average Variance Extracted (AVE) values surpassed the minimum requirement of 0.50 for all constructs, with green entrepreneurial innovation achieving 0.589, green economy transformation reaching 0.627, and sustainable food security attaining 0.613 (see **Table 2**).

Internal consistency reliability was confirmed through multiple indicators, with Cronbach's Alpha coefficients exceeding 0.70 for all constructs. Composite Reliability (CR) values were consistently higher, ranging from 0.864 to 0.891, providing additional confirmation of construct reliability. These reliability measures indicate that the scales demonstrate acceptable internal consistency for structural equation modeling applications (see **Table 2**).

Discriminant validity assessment through the Fornell–Larcker criterion confirmed that the square root of AVE for each construct exceeded its correlations with other constructs, establishing that the constructs are empirically distinct. The HTMT (Heterotrait–Monotrait) ratios provided additional support for discriminant validity, with all values falling below the conservative threshold of 0.85. Multicollinearity assessment revealed no concerning issues, with all Variance Inflation Factor (VIF) values remaining well below the threshold of 5.0.

4.3. Structural Model Results

The direct effect of green entrepreneurial innovation on sustainable food security was positive and statistically significant (β = 0.394, t = 6.847, $p < 0.001$), supporting Hypothesis 1. This finding indicates that

farmers who adopt more green entrepreneurial practices experience enhanced food security outcomes, with a medium to large effect size. Green economy transformation demonstrated a significant positive effect on sustainable food security (β = 0.421, t = 7.293, p < 0.001), providing support for Hypothesis 2. The relationship between green entrepreneurial innovation and green economy transformation was positive and significant (β = 0.668, t = 12.456, p < 0.001), supporting Hypothesis 3 (see **Table 3**).

Table 2. Measurement Model Assessment Results.

Construct	Items	Factor Loadings	Cronbach's α	CR	AVE	√AVE
Green Entrepreneurial Innovation			0.834	0.884	0.589	0.767
	GEI–1	0.751				
	GEI–2	0.782				
	GEI–3	0.724				
	GEI–4	0.778				
	GEI–5	0.803				
	GEI–6	0.752				
	GEI–7	0.789				
	GEI–8	0.744				
Green Economy Transformation			0.852	0.891	0.627	0.792
	GET–1	0.804				
	GET–2	0.781				
	GET–3	0.829				
	GET–4	0.798				
	GET–5	0.742				
	GET–6	0.776				
Sustainable Food Security			0.823	0.864	0.613	0.783
	SFS–1	0.745				
	SFS–2	0.809				
	SFS–3	0.787				
	SFS–4	0.796				
	SFS–5	0.774				
	SFS–6	0.758				

Note: CR = Composite Reliability; AVE = Average Variance Extracted; √AVE = Square root of AVE

Table 3. Structural Model Results and Hypothesis Testing.

Hypothesis	Path	β	SE	t–Value	p–Value	95% CI	f^2	Result
H1	GEI → SFS	0.394	0.058	6.847***	0.000	[0.281, 0.507]	0.247	Supported
H2	GET → SFS	0.421	0.057	7.293***	0.000	[0.309, 0.532]	0.282	Supported
H3	GEI → GET	0.668	0.054	12.456***	0.000	[0.563, 0.774]	0.448	Supported

*Note: GEI = Green Entrepreneurial Innovation; GET = Green Economy Transformation; SFS = Sustainable Food Security; β = standardized path coefficient; SE = standard error; CI = confidence interval; f^2 = effect size. **p < 0.001

The structural model analysis revealed significant relationships consistent with the theoretical framework, explaining substantial variance in the endogenous constructs. The model demonstrated good predictive relevance with R^2 values of 0.447 for green economy transformation and 0.612 for sustainable food security, indicating that the model explains 44.7% and 61.2% of variance in these constructs respectively (see **Table 4**). These effect sizes are considered moderate to large and are consistent with similar studies in agricultural development contexts.

The blindfolding procedure confirmed predictive relevance for the model, with Q^2 values exceeding zero for all endogenous constructs: green economy transformation (Q^2 = 0.267) and sustainable food security (Q^2 = 0.361) (see **Table 4**). These positive Q^2 values indicate that the model has predictive relevance beyond what would be expected by chance, supporting the theoretical framework's utility for understanding and predicting food security outcomes.

Table 4. Model Fit.

Model Fit Indicator	Construct	Value
R^2 (Coefficient of Determination)	Green Economy Transformation	0.447
R^2 (Coefficient of Determination)	Sustainable Food Security	0.612
Q^2 (Predictive Relevance)	Green Economy Transformation	0.267
Q^2 (Predictive Relevance)	Sustainable Food Security	0.361

4.4. Mediation Analysis

The mediation analysis provided strong support for Hypothesis 4, demonstrating that green economy transformation partially mediates the relationship between green entrepreneurial innovation and sustainable food security. **Table 5** presents the comprehensive mediation analysis results, showing the decomposition of effects into direct, indirect, and total components along with their statistical significance and confidence intervals. The specific indirect effect through green economy transformation was positive and statistically significant (β = 0.281, t = 5.923, p < 0.001), with the bias–corrected bootstrap confidence interval [0.187, 0.364] excluding zero, confirming the presence of significant mediation.

The mediation analysis revealed that the direct effect of green entrepreneurial innovation on sustainable food security remained significant when including the mediator (β = 0.394, p < 0.001), while the total effect increased to β = 0.675 (p < 0.001). This pattern indicates partial mediation, where green economy transformation explains part of the relationship between green entrepreneurial innovation and food security, but direct effects also remain important.

The mediation assessment summary is provided in **Table 6**, which confirms the partial mediation type and presents key validation statistics. The Variance Accounted For (VAF) calculation revealed that 41.6% of the total effect of green entrepreneurial innovation on sustainable food security is mediated through green economy transformation, while 58.4% represents direct effects.

Table 5. Mediation Analysis Results.

Effect Type	Path	β	SE	t–Value	p–Value	95% CI	VAF (%)
Direct Effect	GEI → SFS	0.394	0.058	6.847***	0.000	[0.281, 0.507]	58.4
Indirect Effect	GEI → GET → SFS	0.281	0.047	5.923***	0.000	[0.187, 0.364]	41.6
Total Effect	GEI → SFS	0.675	0.051	13.294***	0.000	[0.576, 0.774]	100.0

*Note: GEI = Green Entrepreneurial Innovation; GET = Green Economy Transformation; SFS = Sustainable Food Security; β = standardized coefficient; SE = standard error; CI = bias–corrected bootstrap confidence interval (5,000 iterations); VAF = Variance Accounted For. **p < 0.001

Table 6. Mediation Assessment.

Indicator	Results
Mediation Type	Partial Mediation
VAF (Variance Accounted For)	41.6%
Sobel Test	z = 5.632***

5. Discussion

5.1. Key Findings and Theoretical Contributions

This study provides robust empirical evidence for the complex relationships between green entrepreneurial innovation, green economy transformation, and sustainable food security among Indonesian smallholder farmers, with findings that both confirm and extend existing theoretical frameworks in significant ways. The substantial explanatory power achieved notably exceeds comparable studies in developing country agricultural contexts, such as similar relationships documented in Sub–Saharan Africa by He et al.[12] and ASEAN contexts analyzed by Phan[34]. This enhanced explanatory power suggests that our integrated theoretical framework, combining Resource–Based View theory,

Institutional Theory, and Sustainable Livelihood Framework as proposed by Nandi et al.[38], captures critical dynamics that single–theory approaches may miss.

The strong direct effect of green entrepreneurial innovation on sustainable food security provides important empirical validation for theories linking individual farmer capabilities to household–level outcomes. This relationship strength aligns with recent findings on digital technology applications in sustainable agriculture[7, 8], suggesting that green innovations may generate stronger food security benefits than conventional technological adoptions. The multi–dimensional nature of green innovations simultaneously addresses productivity, environmental sustainability, and economic viability, creating synergistic effects that conventional technologies lack, supporting the Sustainable Innovation 2.0 paradigm articulated by Dyck and Silvestre[39].

Most significantly, the partial mediation finding provides novel theoretical insight into the mechanisms through which individual innovations generate system–level changes that amplify food security benefits. The mediation effect demonstrates that green economy transformation serves not merely as a contextual factor but as an active mediating mechanism that enhances the translation of individual innovations into broader food security outcomes. This finding advances mediation theory in agricultural innovation systems beyond the work of Lema et al.[13] and Su et al.[14], who identified system–level mediation mechanisms but did not quantify their relative importance in food security contexts.

5.2. Comparison with Existing Literature and Regional Context

The findings from Indonesian smallholder farmers provide valuable comparative insights when examined alongside similar studies from other developing country contexts, revealing both consistencies and important divergences that illuminate the context–dependency of innovation–food security relationships. The moderate adoption levels of green entrepreneurial innovation observed in our study reflect regional patterns, where Khan et al.[45] found that Indonesia lags behind Malaysia in green innovation implementation, suggesting significant potential for improvement through targeted interventions.

However, the strength of the relationship between individual innovations and green economy transformation observed in Indonesia ($\beta = 0.668$, $p < 0.001$) appears stronger than relationships documented in more institutionally constrained contexts. This institutional dimension aligns with recent analysis of inclusive green growth dynamics in Asia by Khurshid et al.[31], who found that financial development significantly promotes green growth, though technological innovation impacts vary across regions, supporting our finding that green economy transformation mechanisms are context–dependent and require tailored approaches for different institutional environments.

The complex relationships between individual innovations and food security outcomes observed in our study are consistent with broader Southeast Asian patterns documented by Appelt et al.[46], who found mixed food security outcomes from agricultural changes across the region, highlighting trade–offs between economic gains and sustainability objectives. However, our study demonstrates that when innovations are specifically oriented toward sustainability (green entrepreneurial innovation), these trade–offs may be minimized, supporting the arguments of He et al.[12] that green economic approaches can simultaneously advance multiple development objectives.

5.3. Theoretical Contributions and Advancement of Innovation–Food Security Literature

This study makes several important theoretical contributions that advance understanding of innovation–food security relationships in developing country contexts. The integration of Resource–Based View theory, Institutional Theory, and Sustainable Livelihood Framework demonstrates the value of multi–theoretical approaches in capturing the complexity of agricultural development processes, extending the work of Nandi et al.[38] who argued for such integration but provided limited empirical validation in food security contexts.

The finding that green economy transformation serves as a crucial mediating mechanism provides empirical support for the emerging Sustainable Innovation

2.0 paradigm articulated by Dyck and Silvestre [39], which emphasizes socio–ecological value creation over purely financial outcomes. Our results demonstrate that this theoretical shift has practical implications, as innovations oriented toward broader sustainability objectives generate superior food security outcomes through their enhanced capacity to catalyze economic transformation.

The partial mediation finding also contributes to agricultural innovation systems theory by demonstrating that while individual farmer capabilities remain important (direct effects), their translation into broader outcomes depends critically on intermediate mechanisms that connect individual actions to system–level changes. This extends the multilevel innovation platform theory of Lema et al. [13] by providing quantitative evidence of the relative importance of different pathways through which innovations scale from individual to system levels.

5.4. Methodological Contributions and Research Implications

The research demonstrates several methodological innovations that advance agricultural development research. The successful application of PLS–SEM to examine complex mediation relationships in smallholder agriculture contexts provides a template for future research examining multi–level innovation systems. The integration of validated measurement scales adapted for Indonesian contexts offers tools that can be replicated across different developing country settings.

The achievement of high explanatory power while maintaining methodological rigor suggests that the theoretical framework captures essential dynamics often missed in simpler models. This methodological contribution is particularly significant given the complexity of agricultural innovation systems and the challenges of measuring abstract constructs like green economy transformation in developing country contexts.

5.5. Limitations and Research Considerations

Several methodological limitations must be acknowledged that provide important context for interpreting findings. The cross–sectional design, while appropriate for examining relationships at a specific point in time, cannot establish definitive causality between constructs despite the strong theoretical grounding. The regional focus on Deli Serdang Regency provides valuable context–specific insights but may limit generalizability to other Indonesian regions or developing country contexts with different agro–ecological, economic, or institutional characteristics.

The reliance on self–reported data introduces potential response bias, particularly regarding sensitive topics such as environmental practices and income measures. Common method bias represents a potential concern given the single–source nature of data collection, though the study employed multiple validation procedures and the complexity of the structural model reduces the likelihood that relationships are solely attributable to method effects.

Future research should examine these relationships across diverse agro–ecological zones, different levels of economic development, and varying policy environments to assess the generalizability of findings. Multi–country comparative studies would be particularly valuable for understanding how different institutional and economic contexts influence the relationships between green innovation and food security, while longitudinal studies would strengthen causal inference and enable examination of dynamic relationships over time.

6. Conclusion

6.1. Summary of Key Findings

This study demonstrates that green entrepreneurial innovation enhances sustainable food security among Indonesian smallholder farmers through both direct pathways and indirect mechanisms involving green economy transformation. The research establishes green economy transformation as a crucial mediating mechanism, accounting for 41.6% of the total effect while explaining 61.2% of the variance in sustainable food security outcomes. These findings provide novel empirical evidence for systemic approaches to agricultural development that recognize the interconnected nature of individual innovations and broader economic

transformation processes.

6.2. Practical Implications for Farmers and Agricultural Extension

The research findings offer concrete guidance for enhancing agricultural practice and extension service delivery. For individual farmers, the strong direct effects indicate that adopting environmentally friendly practices, sustainable crop varieties, and green marketing approaches directly improve household food security. Farmers should prioritize integrated approaches that combine green product innovations (organic fertilizers, sustainable varieties) with green process innovations (waste management, chemical reduction) to maximize food security benefits.

Agricultural extension services can leverage these findings by redesigning farmer training programs to emphasize the business and economic dimensions of green innovations, not just their environmental benefits. Extension programs should help farmers understand how their individual innovations contribute to broader economic opportunities, including access to green markets, certification programs, and value chain participation. Extension agents should facilitate connections between individual farmers and green economy opportunities, such as organic certification schemes, sustainable agriculture cooperatives, and environmentally–conscious buyers.

Practical implementation strategies should include demonstration plots showcasing integrated green innovations, farmer–to–farmer learning networks that facilitate knowledge sharing about successful green entrepreneurship practices, and partnerships with financial institutions to support green innovation adoption. The moderate adoption levels observed suggest significant room for improvement through targeted capacity building that addresses both technical and economic dimensions of green innovation.

6.3. Policy Implications and Government Program Recommendations

The substantial mediation effects reveal that policies targeting only individual farmer behavior will achieve limited results without complementary systemic interventions. Governments should develop integrated agricultural development strategies that simultaneously build farmer–level capabilities and create enabling environments for green economy participation.

First, agricultural policy reform should focus on transforming extension services to include green entrepreneurship training, business development support, and market linkage facilitation. Traditional extension approaches focused on technical adoption should be expanded to include economic literacy, environmental stewardship, and value chain participation. Policy frameworks should incentivize integrated approaches that address productivity, sustainability, and economic viability simultaneously.

Second, market development policies should leverage the strong relationship between green innovation and green economy transformation by investing in green market infrastructure, including certification systems, sustainable supply chains, and premium market development. Policies should support the creation of institutional mechanisms that connect individual farmer innovations to broader economic opportunities, such as green procurement programs for government institutions and sustainable agriculture cooperatives.

Third, institutional support systems require dedicated agencies or programs that coordinate between agricultural, environmental, and economic development sectors. Policy frameworks should address regulatory barriers to green innovation adoption while providing incentives for sustainable practice adoption through subsidy programs, tax incentives, and preferential credit access.

Finally, technology and information access policies should improve farmer access to green technologies and information through digital platforms, demonstration centers, and technology transfer programs. The research suggests that technology access is a crucial component of green economy transformation, requiring coordinated investment in rural infrastructure, digital literacy, and information systems that connect farmers to global knowledge networks.

6.4. Sustainable Finance Implications and Investment Opportunities

The demonstrated linkages between green innovation, economic transformation, and food security create significant opportunities for innovative financing mechanisms that can leverage private capital while generating measurable social and environmental returns. The quantified relationships provide the empirical foundation needed for developing evidence–based sustainable finance products tailored to smallholder agriculture in developing countries.

Financial institutions can develop specialized lending products for green entrepreneurial innovations, using the study's findings to assess risk and design appropriate financial instruments. The strong predictive relationships provide metrics that can be incorporated into credit scoring models for sustainable agriculture lending. Banks and microfinance institutions should develop green agriculture portfolios that specifically target the innovation dimensions identified in this research.

The research provides quantitative evidence that investments in green entrepreneurship generate measurable food security outcomes, creating opportunities for impact investors seeking both financial returns and social impact. The mediation findings suggest that investments should target both individual farmer capabilities and broader green economy infrastructure, providing guidance for portfolio construction that maximizes social impact per dollar invested.

The environmental contribution dimension of green economy transformation suggests opportunities for developing payment for ecosystem services schemes that compensate farmers for sustainable practices. The quantified relationships between green innovations and broader economic outcomes provide the measurement framework needed for designing results–based payment systems that link farmer compensation to verified sustainability and food security outcomes.

The study's findings support the development of green bonds specifically targeting smallholder agriculture in developing countries. The demonstrated relationships between green innovation and multiple development outcomes (food security, economic transformation, environmental sustainability) provide the impact measurement framework needed for green bond reporting and verification. Climate finance mechanisms should prioritize integrated approaches that address both adaptation and mitigation objectives through sustainable agriculture investments.

6.5. Future Research Directions and Methodological Advancement

The research opens several important avenues for future investigation that can strengthen both theoretical understanding and practical applications. Longitudinal studies should track the same farmers over multiple growing seasons to understand the dynamic aspects of green economy transformation and identify critical transition points where individual innovations translate into sustained food security improvements.

Multi–country comparative research should test the innovation–food security framework across diverse institutional, economic, and agro–ecological contexts. Comparative studies across different developing countries would help identify universal principles versus context–specific factors, providing more robust guidance for policy adaptation across different settings.

Experimental design and causal inference represent another critical research priority. Randomized controlled trials of green entrepreneurship interventions could provide definitive causal evidence while testing the practical applicability of the theoretical framework. Experimental approaches should test different components of the integrated innovation framework to identify the most cost–effective intervention strategies.

Gender and social equity analysis requires particular attention in future research. The theoretical framework should be extended to explicitly examine how gender, social equity, and power dynamics influence innovation adoption and food security outcomes. Research should investigate whether the relationships observed hold equally across different social groups and identify strategies for ensuring that green innovation benefits reach marginalized populations.

Climate change integration should examine how climate variability and change influence the innovation–food security relationships, particularly

given the increasing importance of adaptation and resilience in agricultural development. Studies should investigate whether green innovations provide enhanced resilience to climate shocks compared to conventional approaches.

Economic impact assessment represents an additional research frontier. Future research should develop more sophisticated economic impact assessment tools that can quantify the broader economic benefits of green innovation adoption, including effects on rural employment, income distribution, and regional economic development. This would strengthen the business case for investment in sustainable agriculture while providing more comprehensive policy guidance.

6.6. Implications for Achieving Sustainable Development Goals

The demonstrated linkages between green innovation, economic transformation, and food security offer concrete pathways for achieving multiple Sustainable Development Goals simultaneously, providing evidence–based strategies for integrated development approaches. The research contributes to SDG 2 (Zero Hunger) by demonstrating specific mechanisms through which agricultural innovations enhance food security, while simultaneously advancing SDG 8 (Decent Work and Economic Growth) through the economic transformation pathways identified.

The environmental dimensions of green entrepreneurial innovation directly contribute to SDG 13 (Climate Action) by promoting sustainable agricultural practices that reduce environmental impact while enhancing productivity. The integration of sustainability dimensions throughout the innovation–food security framework supports SDG 15 (Life on Land) by demonstrating how agricultural development can simultaneously protect and restore terrestrial ecosystems.

For policymakers and development practitioners, the research provides a framework for designing interventions that achieve multiple SDG targets through coordinated action rather than pursuing individual goals in isolation. The quantified relationships provide the measurement framework needed for monitoring progress toward multiple SDGs simultaneously, supporting integrated approaches to sustainable development that maximize synergies while minimizing trade–offs.

The findings also contribute to SDG 17 (Partnerships for the Goals) by demonstrating the importance of coordinated action across sectors, with implications for how governments, the private sector, civil society, and international organizations can collaborate more effectively to support sustainable agricultural development. The research provides empirical evidence for the effectiveness of integrated approaches that combine individual capacity building with systemic transformation, offering guidance for partnership models that can achieve greater impact through coordinated action.

As countries worldwide pursue sustainable development goals while addressing food security challenges, the innovation–transformation–security linkages identified in this research become increasingly critical for evidence–based policy formulation and program design. The research demonstrates that achieving sustainable food security requires coordinated interventions that recognize farmers as active agents of economic transformation rather than passive beneficiaries of top–down interventions, providing a foundation for more effective and sustainable approaches to agricultural development in the 21st century.

Author Contributions

B.A.: Conceptualization, methodology, data collection, formal analysis, writing—original draft preparation, project administration, funding acquisition. S.: Literature review, data validation, writing—review and editing, supervision. C.C.C.: Data collection, statistical analysis, writing—review and editing, visualization. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data supporting the conclusions of this article are available from the corresponding author upon reasonable request. Raw data cannot be shared publicly due to ethical restrictions and privacy concerns of research participants. Requests for access to anonymized datasets should be directed to the corresponding author and will be considered on a case–by–case basis following institutional review.

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Conflicts of Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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