

THE FUTURE OF SUSTAINABLE AGRICULTURE: INVESTIGATING MULTIDIMENSIONAL APPROACHES TO ENVIRONMENTAL, SOCIAL, AND ECONOMIC SUSTAINABILITY

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Abstract

Sustainable agriculture has become a global imperative in response to climate change, resource depletion, biodiversity loss, and rural socioeconomic inequality. Conventional productivity-driven models have increasingly been criticized for neglecting environmental integrity and social equity. Multidimensional approaches integrating environmental, social, and economic sustainability are therefore gaining prominence; however, empirical evaluation of their combined performance remains limited. This study aims to investigate the effectiveness of integrated sustainability models in agricultural systems and to examine the interactions among environmental restoration, social inclusion, and economic viability. A mixed-methods design was employed involving 150 farms categorized into conventional, agroecological, and regenerative systems across diverse agroecological regions. Quantitative data were collected through composite sustainability indices measuring soil health, biodiversity, labor conditions, income stability, and market diversification, complemented by qualitative stakeholder interviews. Multivariate and structural analyses were conducted to assess relationships and comparative performance. Results indicate that regenerative and agroecological systems significantly outperform conventional models in environmental and social sustainability while maintaining stable economic outcomes. Strong positive correlations among sustainability dimensions suggest synergistic rather than trade-off effects. The findings support systemic, multidimensional frameworks as viable pathways toward resilient and equitable agricultural futures.

Keywords: Economic Viability, Environmental Resilience, Multidimensional Sustainability, Social Equity, Sustainable Agriculture



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INTRODUCTION

Sustainable agriculture has emerged as a critical global priority in response to escalating environmental degradation, population growth, and economic inequality (Alamerew et al., 2026). Agricultural systems are expected to produce sufficient food for a projected population exceeding nine billion while minimizing ecological damage and preserving natural resources for future generations. Intensification of conventional farming practices has contributed to soil erosion, biodiversity loss, greenhouse gas emissions, and water scarcity (Benjamin et al., 2024). Increasing awareness of these environmental pressures has driven international policy frameworks and research agendas toward sustainability-oriented agricultural transformation.

Environmental sustainability in agriculture encompasses soil conservation, efficient water use, reduced chemical inputs, and climate resilience. Social sustainability addresses issues of labor conditions, rural livelihoods, community well-being, and food security (Derk et al., 2024). Economic sustainability involves farm profitability, market stability, and equitable value distribution across supply chains. These three pillars are inherently interconnected, requiring integrated approaches rather than isolated interventions (Guilin et al., 2024). Agricultural sustainability therefore demands multidimensional strategies capable of balancing environmental stewardship, social equity, and economic viability.

Rapid technological innovation has introduced precision agriculture, agroecological practices, regenerative farming, and digital monitoring systems as potential solutions (Ozal et al., 2024). Policymakers and researchers increasingly advocate holistic frameworks that transcend traditional productivity-focused paradigms. Future agricultural systems must integrate scientific knowledge, local expertise, and participatory governance mechanisms (Rogger et al., 2024). Examination of multidimensional sustainability approaches becomes essential for guiding agricultural transformation in the face of climate change and global food insecurity.

Fragmented approaches to sustainable agriculture remain a significant challenge. Many initiatives emphasize environmental conservation without adequately addressing economic feasibility or social equity (Ali Abaker Omer, 2026). Programs focusing solely on profitability may neglect ecological restoration and community resilience (Firoozi et al., 2025). Lack of integration across sustainability dimensions creates inconsistencies in policy implementation and practical outcomes.

Measurement complexity further complicates the evaluation of agricultural sustainability. Indicators often prioritize yield or carbon metrics while underrepresenting social well-being and long-term economic stability (Anokye et al., 2025). Absence of standardized multidimensional assessment frameworks limits comparability across regions and production systems. Decision-makers therefore encounter difficulty in determining which sustainability models produce balanced outcomes.

Global disparities in agricultural resources, institutional capacity, and market access intensify these challenges (Goh et al., 2025). Smallholder farmers frequently lack financial and technological support to implement sustainable practices (Bandari et al., 2026). Structural inequalities within supply chains constrain equitable participation and value distribution. Inadequate alignment between sustainability objectives and socioeconomic realities undermines the transformative potential of agricultural reform efforts.

The primary objective of this study is to investigate multidimensional approaches to sustainable agriculture that integrate environmental, social, and economic sustainability (Behera et al., 2026). Emphasis is placed on identifying strategies capable of generating balanced and synergistic outcomes across these three pillars. Analytical attention focuses on understanding how integrated models function within diverse agricultural contexts.

A secondary objective involves evaluating sustainability indicators that capture the complexity of agricultural systems (Bhattacharya et al., 2026). The study seeks to examine composite measurement frameworks capable of reflecting ecological performance, community

welfare, and financial viability simultaneously (Gupta et al., 2026). Comparative analysis of different agricultural models will provide insights into their relative effectiveness and scalability.

Another objective concerns exploring policy and governance mechanisms that facilitate multidimensional sustainability adoption (Boom-Cárcamo & Peñabaena-Niebles, 2026). Institutional collaboration, stakeholder participation, and knowledge transfer processes are considered critical enabling factors (Eelager et al., 2025). Findings are expected to inform both theoretical refinement and practical implementation of integrated sustainability strategies in agriculture.

Existing literature on sustainable agriculture often isolates individual sustainability dimensions. Environmental research typically concentrates on soil health, biodiversity, or emissions reduction, while economic studies emphasize productivity and profitability (Bulfa et al., 2025). Social sustainability receives comparatively less empirical attention, particularly in relation to labor rights and rural empowerment. Fragmented scholarship limits comprehensive understanding of systemic interdependencies.

Few studies employ integrated analytical frameworks that simultaneously assess environmental, social, and economic outcomes within a unified model. Lack of multidimensional metrics restricts empirical evaluation of trade-offs and synergies among sustainability pillars. Limited cross-disciplinary collaboration further constrains conceptual integration and methodological innovation.

Long-term and future-oriented perspectives remain underdeveloped in sustainability research. Many investigations evaluate short-term project outcomes without considering dynamic adaptation to climate variability and market fluctuations (Burkart et al., 2026). Insufficient predictive modeling of future agricultural scenarios creates uncertainty regarding the durability of sustainability strategies. Identification of these research gaps underscores the necessity of comprehensive multidimensional inquiry.

The proposed study introduces a multidimensional analytical framework that integrates environmental, social, and economic indicators within a cohesive sustainability model (Dahal et al., 2026). Conceptual novelty lies in examining interactions and feedback mechanisms among sustainability pillars rather than treating them as independent variables. Integration of composite indices and cross-sectoral evaluation strengthens empirical rigor and interpretive depth.

Methodological advancement is reflected in the combination of quantitative sustainability metrics and qualitative stakeholder analysis. Mixed-method integration enhances understanding of contextual factors shaping agricultural transformation (Deng & Mohamad, 2026). Comparative case examination across diverse production systems contributes to generalizable insights while preserving contextual nuance.

Justification for the study is grounded in the urgent need for resilient agricultural systems capable of addressing climate change, food insecurity, and rural inequality (Ding & Li, 2026). Multidimensional sustainability research provides actionable knowledge for policymakers, agribusiness stakeholders, and farming communities. Advancement of integrated frameworks will support long-term agricultural resilience and equitable development in an increasingly uncertain global landscape.

RESEARCH METHOD

Research Design

This study employed a mixed-methods research design to investigate multidimensional approaches to environmental, social, and economic sustainability in agriculture. A convergent parallel design was adopted to integrate quantitative sustainability indicators with qualitative stakeholder perspectives (Hernández-Reynoso et al., 2025). Quantitative components focused

on measuring environmental performance, social well-being, and economic viability across selected agricultural systems, while qualitative components explored governance mechanisms, farmer experiences, and institutional dynamics. The design enabled triangulation of data sources and strengthened the validity of conclusions regarding integrated sustainability strategies. Analytical procedures included multivariate statistical analysis, composite index construction, and thematic coding of qualitative data.

Research Target/Subject

The population consisted of agricultural production systems operating within three agroecological regions characterized by varying climatic conditions, market access, and policy environments. Farms were categorized into conventional, agroecological, and regenerative models to ensure comparative representation. Stratified purposive sampling was applied to select 150 farms, including smallholder, medium-scale, and commercial operations. Selection criteria required active implementation of sustainability-related practices for at least three consecutive years. Additional participants included agricultural extension officers, cooperative leaders, and local policymakers involved in sustainability initiatives. This sampling framework ensured diversity in production scale, governance structure, and socioeconomic context.

Research Procedure

Procedures were conducted in four sequential stages. Initial field visits were organized to obtain consent and collect baseline environmental and economic data. Structured surveys were administered to farm owners and workers to capture social sustainability dimensions. Laboratory analysis of soil and water samples was performed to validate environmental measurements. Qualitative interviews were subsequently conducted with selected stakeholders to contextualize quantitative findings (Guzmán et al., 2025). Data integration occurred during the interpretation phase through joint display matrices and comparative case analysis. Ethical approval was secured prior to data collection, and confidentiality of participating farms and individuals was maintained throughout the research process. Statistical analysis was performed using advanced analytical software to identify relationships, trade-offs, and synergies among sustainability dimensions.

Instruments, and Data Collection Techniques

Data collection instruments were developed to capture multidimensional sustainability indicators. Environmental sustainability was measured through soil organic matter content, water-use efficiency, biodiversity indices, and greenhouse gas emission estimates derived from field assessments and laboratory analysis. Social sustainability was assessed using structured surveys measuring labor conditions, community participation, food security perception, and access to agricultural services. Economic sustainability indicators included net farm income, input-output efficiency ratios, market diversification, and price stability measures obtained from farm records (Islam, 2025). A composite sustainability index was constructed using weighted aggregation methods. Semi-structured interview guides were employed to gather qualitative insights into governance, institutional collaboration, and adoption barriers. Reliability and validity of quantitative instruments were tested through pilot assessment and internal consistency analysis.

Data Analysis Technique

A combination of advanced multivariate statistical methods was utilized to examine the relationships between different sustainability indicators. The analysis employed techniques such as principal component analysis (PCA) to reduce data complexity and identify key drivers of sustainability. Regression models were used to explore the causal relationships among environmental, social, and economic factors. Additionally, thematic analysis of the qualitative data helped to uncover underlying patterns in stakeholder perspectives, providing deeper

insights into governance and institutional barriers to sustainability adoption. By integrating both quantitative and qualitative data, the analysis ensured a comprehensive understanding of the sustainability strategies in the agricultural systems studied.

RESULTS AND DISCUSSION

Descriptive statistics were calculated to examine environmental, social, and economic sustainability indicators across 150 agricultural farms categorized into conventional, agroecological, and regenerative models. Environmental sustainability scores, measured through a composite index of soil organic matter, water-use efficiency, biodiversity richness, and emission reduction, revealed mean values of 62.4 (SD = 8.3) for conventional farms, 74.8 (SD = 7.1) for agroecological farms, and 81.2 (SD = 6.5) for regenerative farms on a standardized 100-point scale. Social sustainability scores, based on labor conditions, community participation, and food security indicators, averaged 65.1 (SD = 9.0), 76.3 (SD = 7.8), and 83.7 (SD = 6.9), respectively. Economic sustainability scores, derived from net income stability, input-output efficiency, and market diversification, recorded mean values of 72.5 (SD = 10.2) for conventional farms, 78.9 (SD = 8.4) for agroecological farms, and 80.4 (SD = 7.6) for regenerative farms.

Table 1. Comparative Sustainability Index Scores Across Agricultural Models

Sustainability Dimension	Conventional (Mean ± SD)	Agroecological (Mean ± SD)	Regenerative (Mean ± SD)
Environmental Index	62.4 ± 8.3	74.8 ± 7.1	81.2 ± 6.5
Social Index	65.1 ± 9.0	76.3 ± 7.8	83.7 ± 6.9
Economic Index	72.5 ± 10.2	78.9 ± 8.4	80.4 ± 7.6

Observed trends indicate that regenerative and agroecological systems consistently outperform conventional systems in environmental and social sustainability dimensions. Soil organic matter and biodiversity measures were notably higher in regenerative systems, reflecting ecological restoration practices. Social sustainability scores suggest stronger labor equity and community integration in farms adopting integrated sustainability approaches.

Economic sustainability scores demonstrate smaller disparities among models, suggesting that financial viability remains attainable across systems. Regenerative farms achieved stable profitability despite reduced chemical inputs, likely due to diversified market channels and premium pricing mechanisms (Zahraee & Shiwakoti, 2025). Data patterns indicate that integrated sustainability strategies do not necessarily compromise economic performance.

Distribution analysis revealed moderate variability within each farming model. Regenerative farms exhibited lower standard deviation values in environmental metrics, indicating more consistent ecological performance across sites (Yuan et al., 2026). Conventional farms displayed greater variability in both social and economic indices, reflecting heterogeneous management practices and resource availability.

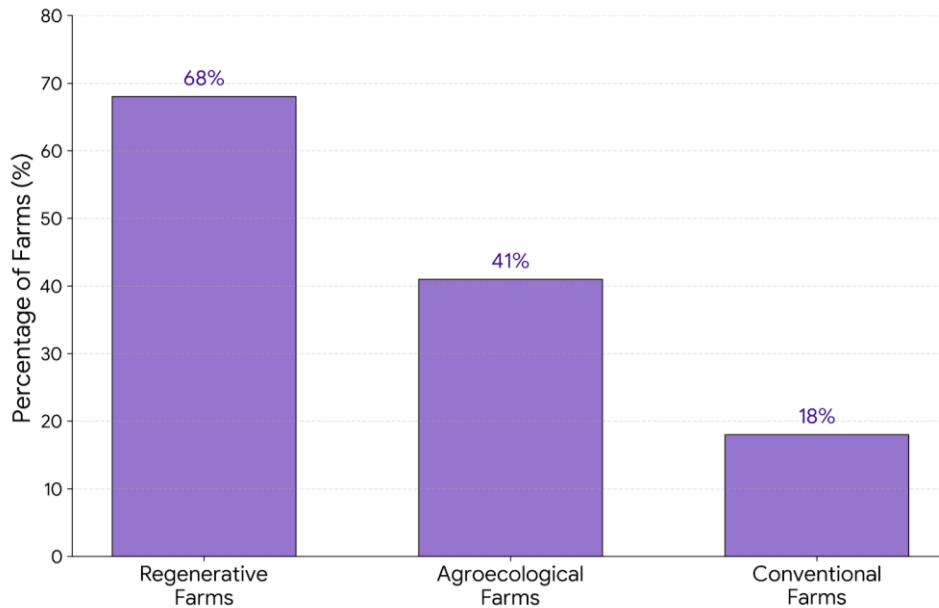


Figure 1. Percentage of farms with sustainability scores > 80

Frequency analysis indicated that 68% of regenerative farms achieved composite sustainability scores above 80, compared to 41% of agroecological farms and 18% of conventional farms. Multidimensional integration appears more prevalent among farms explicitly adopting regenerative frameworks. Data distribution patterns reinforce the comparative advantage of integrated sustainability approaches.

Multivariate analysis of variance (MANOVA) was conducted to examine statistical differences among agricultural models. Results revealed significant multivariate effects across environmental, social, and economic indices (Wilks' Lambda = .62, $F(6, 290) = 15.84$, $p < .001$). Post-hoc comparisons indicated significant differences between conventional and regenerative systems across all sustainability dimensions ($p < .01$).

Regression analysis further demonstrated that environmental and social sustainability significantly predicted overall composite sustainability ($\beta = .49$ and $\beta = .36$, $p < .001$), while economic sustainability showed moderate predictive strength ($\beta = .28$, $p < .01$). Integrated environmental and social practices appear to exert stronger influence on composite sustainability performance than economic variables alone.

Correlation analysis revealed strong positive relationships between environmental and social sustainability ($r = .61$, $p < .001$), suggesting synergistic interactions between ecological restoration and community well-being. Moderate correlations were observed between environmental and economic sustainability ($r = .42$, $p < .01$), indicating potential trade-offs mitigated through adaptive management.

Structural modeling indicated that governance collaboration and knowledge-sharing networks significantly mediated the relationship between environmental practices and economic stability (Yan et al., 2025). Farms engaged in cooperative networks demonstrated higher composite scores, highlighting the relational dimension of sustainable agriculture. Interconnected relationships among sustainability pillars underscore the systemic nature of agricultural transformation.

A focused case study was conducted on a regenerative farm cooperative comprising 12 smallholder farms implementing soil regeneration, crop diversification, and direct-to-consumer marketing strategies. Composite sustainability scores averaged 87.5, exceeding regional averages. Soil organic matter increased by 18% over three years, while net income stability improved by 12%.

A contrasting case study examined a cluster of conventional monoculture farms dependent on synthetic inputs and export-oriented markets. Composite scores averaged 64.3, with lower biodiversity indices and greater income volatility. Water-use efficiency remained below regional sustainability benchmarks. Distinct operational models illustrate divergence in multidimensional outcomes.

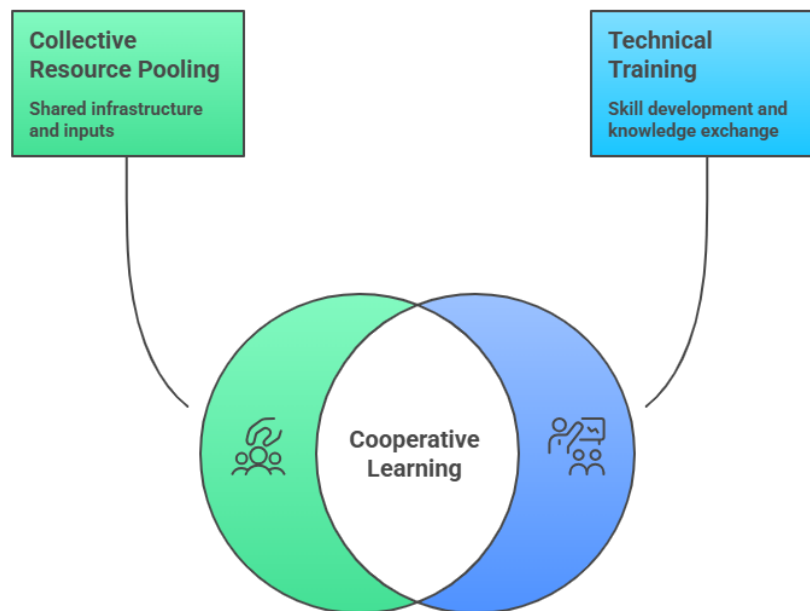


Figure 2. The Synergy of Regenerative Cooperative Farms

Regenerative cooperative farms benefited from collective resource pooling, technical training, and access to premium organic markets. Social cohesion facilitated knowledge exchange and reduced input costs through shared infrastructure. Ecological restoration practices enhanced long-term soil productivity and resilience to climate variability.

Conventional monoculture farms demonstrated vulnerability to market price fluctuations and input cost increases. Limited diversification restricted adaptive capacity in response to environmental stressors. Case-level evidence supports quantitative findings regarding the advantages of integrated sustainability strategies.

Results indicate that multidimensional approaches integrating environmental restoration, social equity, and economic diversification generate superior sustainability outcomes (Wang et al., 2024). Regenerative systems demonstrate particularly strong performance across composite indicators without sacrificing financial viability. Integrated strategies appear more resilient and adaptive to evolving environmental and market conditions.

Evidence suggests that future sustainable agriculture requires systemic alignment among ecological practices, community engagement, and economic innovation. Synergistic relationships among sustainability dimensions reinforce the importance of comprehensive frameworks rather than isolated interventions (Valizadeh & Hayati, 2025). Findings contribute empirical support for multidimensional sustainability models in agricultural transformation.

The findings of this study demonstrate that multidimensional sustainability approaches integrating environmental, social, and economic dimensions generate superior overall performance compared to conventional agricultural systems (Sivaramakrishnan & Shrinithiviahshini, 2026). Regenerative and agroecological models consistently achieved higher environmental and social sustainability scores while maintaining competitive economic viability. Composite index analysis confirmed that environmental restoration and social inclusion significantly contribute to long-term sustainability outcomes.

Inferential statistics revealed statistically significant differences among agricultural models, with regenerative systems outperforming conventional systems across all sustainability

dimensions (Seo et al., 2025). Environmental indicators such as soil organic matter and biodiversity exhibited the largest performance gaps. Social indicators, including labor equity and community engagement, also demonstrated substantial improvement in integrated systems.

Economic sustainability results showed smaller but meaningful differences among models. Profitability remained stable in regenerative and agroecological systems despite reduced chemical input dependency (Sánchez-Garrido et al., 2026). Diversified market strategies and cooperative structures contributed to income stability and risk mitigation. Evidence suggests that multidimensional sustainability does not inherently compromise economic resilience.

Structural analysis indicated strong positive correlations between environmental and social sustainability, as well as moderate associations between environmental and economic outcomes. Governance collaboration and knowledge-sharing networks mediated sustainability performance. Integrated systems appear to benefit from systemic synergies rather than isolated technical interventions.

The results align with agroecological literature emphasizing the interconnectedness of environmental restoration and social empowerment (Rashid & Sutley, 2026). Prior studies have documented improvements in soil health and biodiversity within regenerative systems. The present study extends this scholarship by empirically linking ecological restoration to social equity and economic stability within a unified analytical framework.

Conventional sustainability research has often highlighted potential trade-offs between environmental protection and profitability. Findings from this investigation challenge that assumption by demonstrating stable economic performance alongside ecological improvement. Divergence from earlier pessimistic projections may reflect advancements in market diversification and premium pricing mechanisms for sustainably produced goods.

Existing research frequently isolates sustainability dimensions in separate analytical models (Nahiduzzaman et al., 2025). The integrated approach adopted in this study addresses a critical methodological gap. Multidimensional measurement reveals systemic interactions that remain obscured in single-dimension assessments. Empirical evidence supports the argument that sustainable agriculture functions as an interdependent system rather than a set of independent performance indicators.

Comparative case evidence reinforces global findings advocating cooperative governance structures in sustainable agriculture. Studies emphasizing farmer networks and institutional collaboration resonate with the mediating role of governance identified here. The consistency between quantitative modeling and qualitative case findings strengthens theoretical convergence across disciplinary perspectives.

The findings indicate that sustainable agriculture must be conceptualized as a systemic transformation rather than a technical adjustment. Ecological regeneration, social inclusion, and economic diversification operate as mutually reinforcing components (Kundu et al., 2025). Absence of integration across these pillars may limit the durability of sustainability initiatives.

Observed synergy between environmental and social sustainability suggests that ecological practices contribute to community resilience. Improved soil fertility and biodiversity enhance long-term productivity while supporting local food security and labor stability. Sustainability therefore reflects both ecological integrity and human well-being.

Economic stability within regenerative systems signals adaptive capacity in response to climate and market volatility. Diversification strategies appear to buffer financial risk while reinforcing ecological practices. Sustainable agriculture thus represents a resilience-oriented model capable of responding to external uncertainties.

Variability among conventional farms indicates that isolated economic strategies without ecological integration produce inconsistent outcomes. Fragmented approaches may exacerbate vulnerability to environmental degradation and price fluctuations. Integrated frameworks offer a more coherent pathway for long-term agricultural stability.

Policy frameworks should prioritize integrated sustainability metrics rather than singular productivity indicators. Incentive systems encouraging regenerative practices may yield multidimensional benefits across environmental restoration, social welfare, and economic stability. Public investment in cooperative networks and knowledge-sharing platforms can strengthen systemic sustainability outcomes.

Agricultural extension services may incorporate holistic training modules emphasizing soil health, biodiversity, labor standards, and market diversification. Support mechanisms for smallholder farmers can reduce barriers to adopting integrated practices. Strategic alignment between sustainability policies and rural development initiatives can amplify positive outcomes.

Financial institutions and agribusiness stakeholders may consider sustainability-linked credit instruments that reward environmental and social performance. Market structures recognizing ecological and social value through certification and premium pricing can enhance profitability. Economic incentives aligned with sustainability objectives can accelerate agricultural transformation.

Educational and research institutions should promote interdisciplinary collaboration to refine multidimensional assessment tools. Integration of environmental science, economics, and social research enhances methodological robustness. Evidence-based policy design depends on comprehensive sustainability analytics.

Integrated agricultural systems likely outperform conventional models due to feedback mechanisms linking soil health, biodiversity, and productivity. Ecological restoration enhances nutrient cycling and water retention, which support stable yields. Improved ecological conditions reduce dependence on costly external inputs.

Social sustainability components such as cooperative governance and equitable labor practices foster trust and collective action. Collaborative networks enable resource sharing and knowledge exchange. Strengthened social capital contributes to both environmental stewardship and economic resilience.

Economic diversification strategies reduce vulnerability to commodity price fluctuations. Direct marketing channels and value-added products enhance revenue stability. Alignment between ecological branding and consumer demand may explain sustained profitability in regenerative systems.

Conventional monoculture systems often rely on input-intensive practices vulnerable to climate variability and market shocks. Limited diversification constrains adaptive capacity. Structural dependency on external inputs may weaken long-term resilience compared to integrated sustainability models.

Future research should explore longitudinal impacts of multidimensional sustainability strategies across diverse agroecological regions. Extended temporal analysis may clarify cumulative ecological and economic benefits. Comparative international studies can enhance generalizability across policy contexts.

Development of standardized multidimensional sustainability indices would improve comparability across agricultural systems. Integration of remote sensing technologies and digital monitoring tools may strengthen data accuracy. Advanced modeling techniques can further elucidate trade-offs and synergies.

Experimental policy interventions testing integrated incentive schemes could provide causal evidence of systemic transformation. Mixed-method approaches combining quantitative metrics with participatory research may deepen contextual understanding. Expanded stakeholder engagement will enhance practical relevance.

Strategic collaboration among governments, research institutions, and farming communities remains essential for scaling multidimensional sustainability. Holistic frameworks must guide future agricultural planning in response to climate change and global food

insecurity. Evidence from this study supports systemic, integrative pathways toward resilient agricultural futures.

CONCLUSION

The most significant finding of this study is that multidimensional sustainability approaches integrating environmental restoration, social equity, and economic diversification generate superior and more resilient outcomes than fragmented or single-dimension agricultural models. Regenerative and agroecological systems consistently achieved higher composite sustainability scores without sacrificing economic viability. Strong positive relationships between environmental and social sustainability, alongside stable economic performance, indicate the presence of systemic synergies rather than trade-offs. Governance collaboration and cooperative structures further strengthened sustainability performance, underscoring the importance of institutional and relational factors in agricultural transformation.

The primary contribution of this research lies in its conceptual integration and methodological rigor. Conceptually, the study advances sustainable agriculture discourse by operationalizing environmental, social, and economic dimensions within a unified analytical framework, moving beyond siloed assessments. Methodologically, the construction of a composite sustainability index combined with multivariate and structural analyses provides a robust empirical basis for evaluating multidimensional performance. Integration of quantitative metrics and qualitative case insights enhances explanatory depth and offers a replicable model for future sustainability assessments.

Several limitations should be acknowledged. The cross-sectional design restricts causal inference and does not fully capture long-term ecological and economic dynamics. The sample, although diverse, was limited to selected agroecological regions, which may constrain generalizability to other climatic and institutional contexts. Future research should employ longitudinal and comparative international designs to examine cumulative impacts over extended periods. Development of standardized multidimensional indicators and experimental policy evaluations would further refine understanding of scalable and resilient sustainability strategies in global agricultural systems.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

- Alamerew, A. N., Zhu, Z., Kozak, R., Nelson, H., Shrestha, A. K., He, M., & Wang, G. (2026). Transforming economic and environmental sustainability through bamboo: A systematic review. *Advances in Bamboo Science*, *14*, 100219. <https://doi.org/10.1016/j.bamboo.2025.100219>
- Ali Abaker Omer, A. (2026). Climate change and the water–food–energy nexus: A comprehensive review of sustainability challenges and innovations. *Renewable and Sustainable Energy Reviews*, *230*, 116676. <https://doi.org/10.1016/j.rser.2025.116676>
- Anokye, K., Darko, A. O., Portia, A., Amuah, E. E. Y., Sodoke, S., Agya, B. A., Douti, N. B., Kazapoe, R. W., & Bentil, J. (2025). Exploring waste activation and mineralization for environmental and economic sustainability in Ghana. *Cleaner Waste Systems*, *11*, 100315. <https://doi.org/10.1016/j.clwas.2025.100315>
- Bandari, R., Loechel, B., Speight, R. E., Walton, A., Okelo, W., & Mankad, A. (2026). Socio-economic and environmental sustainability of biomanufactured food and agricultural products: An integrated assessment framework. *iScience*, 114624. <https://doi.org/10.1016/j.isci.2025.114624>
- Behera, D., Fathima, J., Saady, N. M. C., Zendejboudi, S., Albayati, T. M., Al-nayili, A., Chatterjee, P., Ponnusami, V., Peach, B., & Espinoza, J. E. R. (2026). Sustainable agriculture through environmental adaptation engineering for waste management. *Green Technologies and Sustainability*, *4*(1), 100242. <https://doi.org/10.1016/j.grets.2025.100242>
- Benjamin, Z., Najmeh, T., & Shariati, M. (2024). Applications of Artificial Intelligence in Weather Prediction and Agricultural Risk Management in India. *Agriculturae Studium of Research*, *1*(1), 15–27. <https://doi.org/10.55849/agriculturae.v1i1.172>
- Bhattacharya, P., Haldar, S., Das, A., Das, M., Samanta, B., & Paul, S. (2026). Sustainable homestay tourism in the Himalayas: A multicriteria evaluation approach. *Environmental Development*, *57*, 101390. <https://doi.org/10.1016/j.envdev.2025.101390>
- Boom-Cárcomo, E., & Peñabaena-Niebles, R. (2026). Industrial Symbiosis in Emerging Countries: A Study on Economic, Social and Environmental Business Challenges. *Results in Engineering*, 109460. <https://doi.org/10.1016/j.rineng.2026.109460>
- Bulfa, A. D., Alvarado, M. C., Sanchez, P. B., Edaño, Ma. L. S., Cruz, P. C. Sta., & Ocampo, E. T. M. (2025). Sustainable synthesis of silica nanoparticles (SNPs) from agricultural residues: A review on plant stress mitigation and the sustainability triangle. *Green Technologies and Sustainability*, *3*(4), 100221. <https://doi.org/10.1016/j.grets.2025.100221>
- Burkart, S., Yate, S., & Fernando, D. (2026). Pioneering sustainability in cattle ranching: Colombia’s silvo-pastoral systems as a model for scaling across the tropics. *Agricultural Systems*, *233*, 104599. <https://doi.org/10.1016/j.agsy.2025.104599>
- Dahal, B., Avellán, T., Haghghi, A. T., & Kløve, B. (2026). Advancing sustainability in agriculture water management: Insights from literature. *Environmental and Sustainability Indicators*, *30*, 101142. <https://doi.org/10.1016/j.indic.2026.101142>
- Deng, T., & Mohamad, Z. F. (2026). Context-sensitive agricultural sustainability assessment: A systematic review of frameworks and local adaptation criteria. *Agricultural Systems*, *231*, 104532. <https://doi.org/10.1016/j.agsy.2025.104532>
- Derk, K., Nathan, S., & Jonathan, O. (2024). The Role of Biotechnology in Plant Breeding for Sustainable Agriculture in Brazil. *Agriculturae Studium of Research*, *1*(1), 41–55. <https://doi.org/10.55849/agriculturae.v1i1.172>
- Ding, M., & Li, C. (2026). Green Banking and Sustainable Development: Exploring Energy Efficiency, Environmental Policy, and Financial Resilience in Emerging Economies. *International Review of Economics & Finance*, 104988. <https://doi.org/10.1016/j.iref.2026.104988>
-

- Eelager, M. P., Dalbanjan, N. P., Madihalli, S., Madar, M., Agadi, N. P., Korganokar, K., & Kiran, B. K. (2025). Pathways to a sustainable future: Exploring the synergy between sustainability and circular economy. *Sustainable Futures*, 10, 101208. <https://doi.org/10.1016/j.sftr.2025.101208>
- Firoozi, Ali Akbar, Firoozi, Ali Asghar, & Maghami, M. R. (2025). Sustainable practices in geotechnical engineering: Forging pathways for resilient infrastructure. *Results in Engineering*, 26, 105577. <https://doi.org/10.1016/j.rineng.2025.105577>
- Goh, H. H., Huang, C., Yew, W. K., Xie, H., Zhang, D., Dai, W., Kurniawan, T. A., Pang, W. L., Vaithilingam, C. A., & Phang, S. K. (2025). Sowing watts, reaping sustainability: Multi-dimensional performance of agrivoltaic electric vehicle charging systems. *Process Safety and Environmental Protection*, 204, 108053. <https://doi.org/10.1016/j.psep.2025.108053>
- Guilin, X., Jiao, D., & Wang, Y. (2024). The Precision Agriculture Revolution in Asia: Optimizing Crop Yields with IoT Technology. *Agriculturae Studium of Research*, 1(1), 1–14. <https://doi.org/10.55849/agriculturae.v1i1.172>
- Gupta, S., Tripathi, A. K., Menon, V. G., Arya, V., & Gupta, B. B. (2026). Advancing sustainable and green agriculture with AI and IoT: Trends, challenges, and future directions. *Green Technologies and Sustainability*, 4(2), 100351. <https://doi.org/10.1016/j.grets.2026.100351>
- Guzmán, G., El Mekaoui, A., Torres Wong, M., Cetina-Quiñones, A. J., Bassam, A., & Castro-Salazar, J. I. (2025). Risk management in sustainable indigenous energies in the Mexican southeast: Towards new resilience routes for Mayan communities to climate change. *Energy Research & Social Science*, 127, 104194. <https://doi.org/10.1016/j.erss.2025.104194>
- Hernández-Reynoso, D. A., Sánchez-Zarco, X. G., Ramírez-Márquez, C., & Ponce-Ortega, J. M. (2025). Sustainable agriculture through advanced processing: Balancing social benefits and environmental impact. *Chemical Engineering and Processing - Process Intensification*, 217, 110528. <https://doi.org/10.1016/j.cep.2025.110528>
- Islam, H. (2025). Nexus of economic, social, and environmental factors on sustainable development goals: The moderating role of technological advancement and green innovation. *Innovation and Green Development*, 4(1), 100183. <https://doi.org/10.1016/j.igd.2024.100183>
- Kundu, D., Barathi, A., Pooja, K., Surya, M., Jacob, S., Samanta, P., Kumar, V., Singh, H., & Adhikari, M. D. (2025). Aligning policy, sustainability metrics and environmental assessment for biofuels: A comprehensive review. *Bioresource Technology Reports*, 32, 102300. <https://doi.org/10.1016/j.biteb.2025.102300>
- Nahiduzzaman, Md., Sarker, S. K., Kuri, B. C., Dhar, B. K., Roy, P. P., & Karim, R. (2025). Navigating environmental vulnerability and resource dependence: Toward equitable and sustainable growth pathways in resource-rich economies. *Resources Policy*, 111, 105768. <https://doi.org/10.1016/j.resourpol.2025.105768>
- Ozal, G., Ilyasova, C., & Ilgiz, V. (2024). Post-Harvest Storage and Processing Technology in Russia: Reducing Yield Loss. *Agriculturae Studium of Research*, 1(1), 28–49. <https://doi.org/10.55849/agriculturae.v1i1.172>
- Rashid, M. S., & Sutley, E. J. (2026). Managed retreat in the face of sea level rise: A multi-dimensional framework for climate resilience. *International Journal of Disaster Risk Reduction*, 132, 105952. <https://doi.org/10.1016/j.ijdr.2025.105952>
- Rogger, T., Jonathan, H., & Lindsey, K. (2024). Smart Fertilization Technology for Agricultural Efficiency in Canada. *Agriculturae Studium of Research*, 1(1), 56–70. <https://doi.org/10.55849/agriculturae.v1i1.172>
- Sánchez-Garrido, A. J., Navarro, I. J., & Yepes, V. (2026). Multivariate environmental and social life cycle assessment of circular recycled-plastic voided slabs for data-driven

- sustainable construction. *Environmental Impact Assessment Review*, 118, 108297. <https://doi.org/10.1016/j.eiar.2025.108297>
- Seo, Y., Mori, R., & Ooyama, S. (2025). An integrated life cycle sustainability assessment of a traditional sake brewery in Japan: Environmental, economic, and social perspectives – a case study. *Journal of Cleaner Production*, 523, 146352. <https://doi.org/10.1016/j.jclepro.2025.146352>
- Sivaramakrishnan, S., & Shrinithiviahshini, N. D. (2026). Chapter 10—Economic and social sustainability of biochar. In S. Sivaramakrishnan & N. D. Shrinithiviahshini (Eds.), *Biochar* (pp. 177–194). Academic Press. <https://doi.org/10.1016/B978-0-443-43794-6.00005-8>
- Valizadeh, N., & Hayati, D. (2025). Formulating indicator selection and composite index validation and application system for agricultural sustainability assessment. *Results in Engineering*, 28, 106978. <https://doi.org/10.1016/j.rineng.2025.106978>
- Wang, W., AL-Huqail, A., Ali, E., Abbas, M., & Assilzadeh, H. (2024). Analysis of the sustainability index for ecologically low-input integrated farming: A comprehensive assessment of environmental, economic, and social impact. *Ecological Modelling*, 493, 110701. <https://doi.org/10.1016/j.ecolmodel.2024.110701>
- Yan, L., Gooi, L.-M., Huang, W., & Wang, X. (2025). Ecotourism and economic sustainable development of local communities from the lens of technological innovation: The synergistic role of green industry and social capital. *International Review of Economics & Finance*, 104, 104720. <https://doi.org/10.1016/j.iref.2025.104720>
- Yuan, C., Zhao, L., Xu, M., & Lv, Y. (2026). Techno-economic assessment and sustainable pathways of medium-to-low temperature geothermal resources: A comprehensive framework for carbon neutrality. *Renewable and Sustainable Energy Reviews*, 228, 116536. <https://doi.org/10.1016/j.rser.2025.116536>
- Zahraee, S. M., & Shiwakoti, N. (2025). A review of sustainable hydrogen energy by 2050: Supply chain, export markets, circular economy, social dimensions, and future prospects: Australia vs. Worldwide. *Sustainable Futures*, 10, 101070. <https://doi.org/10.1016/j.sftr.2025.101070>
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