

Sustainable Agricultural Practices For Climate Change Mitigation: Balancing Productivity And Environmental Conservation

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Abstract

Background: Sustainable agricultural practices play a critical role in mitigating climate change while maintaining agricultural productivity and environmental conservation. Climate-smart agriculture (CSA), conservation agriculture, agroforestry, and precision farming are among the key strategies that enhance crop yields, reduce greenhouse gas emissions, and improve soil health.

Objective: This study examines the impact of sustainable agricultural practices on climate change mitigation and assesses the role of government policies and technological advancements in their adoption. It also explores the barriers to widespread implementation and their effects on productivity and environmental sustainability.

Methods: A quantitative research design was employed using structural equation modeling (SEM) to analyze the relationships between government incentives, technology adoption, and farmers' sustainability knowledge. Data were collected from farmers practicing sustainable agriculture across different regions.

Findings: Results indicate that government policies and technological advancements significantly drive the adoption of sustainable practices. However, excessive reliance on external incentives or automation may reduce farmers' engagement in sustainability learning. The study also finds that sustainable practices improve agricultural resilience, soil quality, and climate adaptation.

Conclusion: Balanced interventions integrating sustainability education, policy support, and technological innovations are essential for long-term food security and environmental conservation. Future strategies should focus on overcoming socio-economic barriers to enhance adoption.

Keywords: Sustainable agriculture, climate-smart agriculture, agroforestry, conservation agriculture, precision farming, climate change mitigation, agricultural productivity, environmental sustainability.

INTRODUCTION:

Sustainable agricultural practices play a crucial role in mitigating climate change while maintaining productivity and conserving the environment. These practices aim to enhance crop yields, farm incomes, and food security while reducing greenhouse gas emissions and promoting ecosystem resilience. Climate-smart agriculture (CSA) is a key strategy that integrates sustainable techniques such as conservation agriculture, crop diversification, and agroforestry to ensure stable yields amid erratic weather patterns

(Uebersax et al., 2023) . Interestingly, while industrial agriculture has been instrumental in addressing global food demands, it has also led to detrimental externalities such as deforestation, biodiversity loss, and soil degradation (Comolli et al., 2024). In contrast, sustainable practices like agroforestry leverage biodiversity and ecosystem services to tackle both adaptation and mitigation challenges (Raihan & Tuspekova, 2022) . For instance, an integrated agroforestry system for yerba mate cultivation in Argentina has demonstrated soil preservation, productivity comparable to or exceeding monocultures, and increased resiliency during extreme climate events (Saleem et al., 2024) . In conclusion, sustainable agricultural practices offer a win-win strategy for combating climate change and conserving natural resources (Reddy, Hariram, Ghazali, & Kumarasamy, 2024). These practices not only improve soil health, water retention, and biodiversity but also contribute to climate change mitigation by reducing agriculture's carbon footprint (Koutouleas et al., 2022) . The integration of sustainable agriculture practices into rural development policy frameworks is crucial for improving livelihoods and ensuring long-term food security (Farooq et al., 2022) . As we strive to meet the Sustainable Development Goals and keep global warming below 2°C, it is essential to identify and exploit synergies between productivity, adaptation, and mitigation in agriculture (Olorunfemi, Olufayo, Fasinmirin, & Komolafe, 2022).

Sustainable agricultural practices for climate change mitigation focus on balancing productivity and environmental conservation through various strategies that enhance crop yields, reduce greenhouse gas emissions, and improve soil health. These practices aim to address the challenges posed by climate change while ensuring food security and preserving natural resources. Climate-smart agriculture (CSA) is a key approach that combines sustainable farming techniques with climate change adaptation and mitigation strategies. CSA practices include conservation agriculture, crop diversification, agroforestry, and precision farming, which have been shown to improve soil fertility, water retention, and overall agricultural resilience. These methods not only enhance productivity but also contribute to carbon sequestration and reduced greenhouse gas emissions. Interestingly, some studies have found that sustainable farming practices can lead to higher outputs, yields, and returns compared to conventional methods . For instance, a long-term study in a humid tropical island demonstrated significant increases in on-farm productivity and net returns through the adoption of CSA practices (Thakur et al., 2023) . However, the implementation of these practices often faces technical and socio-economic barriers, highlighting the need for stronger policy measures and support systems. In conclusion, sustainable agricultural practices for climate change mitigation encompass a wide range of techniques that aim to balance productivity with environmental conservation. These include climate-smart agriculture, conservation agriculture, agroforestry, and precision farming. While these practices have shown promising results in terms of improving yields, soil health, and climate resilience, their widespread adoption requires continued research, policy support, and efforts to overcome implementation barriers (Rahman, Jama Ali, & Raihan, 2022) .

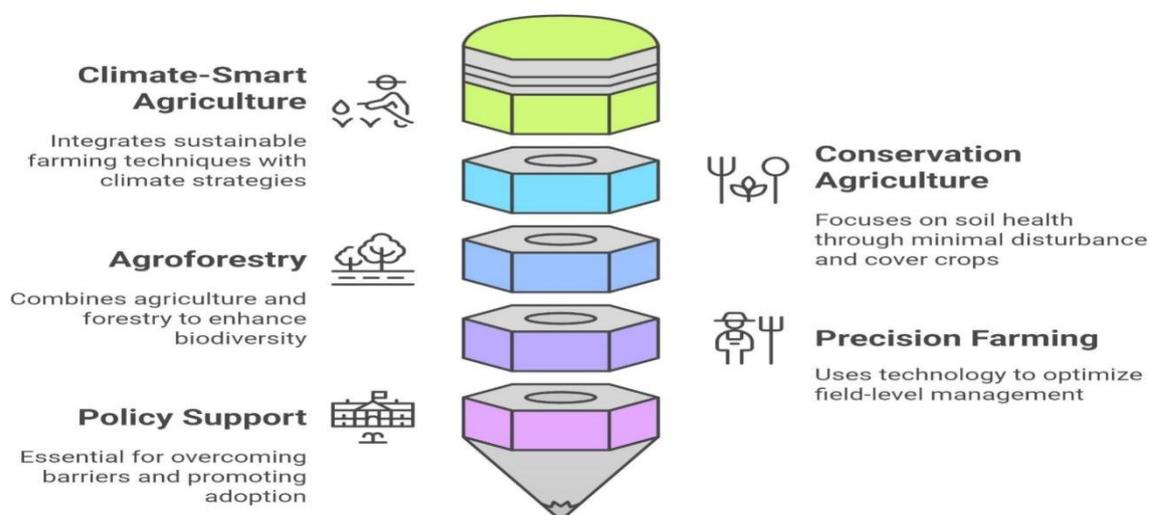
Sustainable Agricultural Practices for Climate Change Mitigation: Balancing Productivity and Environmental Conservation is necessary due to the increasing threats posed by climate change to agricultural productivity, food security, and environmental sustainability. Climate change has significant negative impacts on biodiversity, agricultural sustainability, ecosystems, and economic and social structures, all of which are vital for human resilience and wellbeing. Intensive agriculture contributes to land degradation, pollution, soil erosion, fertility loss, biodiversity decline, and greenhouse gas emissions, exacerbating climate change . These challenges necessitate the adoption of sustainable agricultural practices that can address multiple issues simultaneously (Wei et al., 2024) . Sustainable agricultural practices, such as climate-smart agriculture (CSA), offer a promising approach to mitigate climate change impacts while maintaining or improving agricultural productivity. CSA aims to lower greenhouse gas emissions, strengthen climate change resilience, and raise crop production and incomes significantly. It integrates techniques like conservation agriculture, crop diversification, and agroforestry, which help ensure stable yields even amid erratic weather patterns (He & Rosa, 2023) . Additionally, practices such as reduced tillage, growing cover crops, and implementing crop residue retention measures can enhance soil organic carbon sequestration, improving soil health and increasing agroecosystem resilience to global change . In conclusion, sustainable agricultural practices are essential for balancing productivity and environmental conservation in the face of climate change (Mandal et al., 2022) . These practices not only help in mitigating greenhouse gas emissions but also improve agricultural resilience, enhance food security, and contribute to the achievement of multiple Sustainable Development Goals . By adopting sustainable practices, farmers can achieve higher output, yield, and returns compared to conventional

methods , while also addressing the urgent need for climate change adaptation and mitigation in the agricultural sector (Cárceles Rodríguez et al., 2022) .

Research on sustainable agricultural practices for climate change mitigation reveals a complex interplay between productivity and environmental conservation. While numerous studies highlight the potential of climate-smart agriculture (CSA) in enhancing crop yields, farm incomes, and reducing greenhouse gas emissions , there are still significant research gaps that need to be addressed. One notable contradiction is the varying impact of CSA practices across different regions and farming systems. While some studies report substantial improvements in agricultural productivity and climate resilience , others emphasize the need for more location-specific research to effectively promote and implement these practices as pest management strategies (Khalid et al., 2023) . This highlights the importance of context-specific studies to understand the effectiveness of CSA practices in different agro-ecological zones. In conclusion, future research should focus on integrating advanced technologies like artificial intelligence and machine learning with real-time environmental sensing to develop dynamic frameworks for agricultural management. Additionally, there is a need for more studies that explicitly test pest and predator responses to agricultural practices under climate change conditions. Addressing financial and institutional barriers to the adoption of GHG mitigating agricultural practices is also crucial . Furthermore, exploring the potential of digital agriculture in mitigating climate change impacts and ensuring food security requires a concerted effort from policymakers, researchers, and farmers (Wesseler, 2022) .

Sustainable agricultural practices offer significant potential for climate change mitigation while balancing productivity and environmental conservation. These practices can enhance agricultural resilience, improve soil health, and reduce greenhouse gas emissions . Conservation agriculture (CA), which includes minimum soil disturbance, permanent soil cover, and crop diversification, has been shown to improve soil properties crucial for maintaining soil health and increasing agroecosystem resilience to global change (Khan et al., 2024) . Similarly, climate-smart agriculture (CSA) strategies have demonstrated the ability to enhance on-farm productivity, increase net returns, and reduce greenhouse gas emissions . Interestingly, while the benefits of sustainable practices are well-documented, there are still barriers to their widespread adoption. Technical and socio-economic constraints limit the implementation of CA principles worldwide. Additionally, farmers' knowledge and attitudes towards climate risks play a crucial role in the adoption of climate change mitigation and adaptation practices (Fujimori et al., 2022) . In conclusion, sustainable agricultural practices offer a promising approach to balancing productivity and environmental conservation in the face of climate change. However, their successful implementation requires addressing adoption barriers, enhancing farmers' knowledge, and creating supportive policy frameworks. Integrating these practices into rural development policies and promoting social learning spaces for knowledge sharing could significantly contribute to agricultural sustainability and climate change mitigation efforts (Duan et al., 2024) .

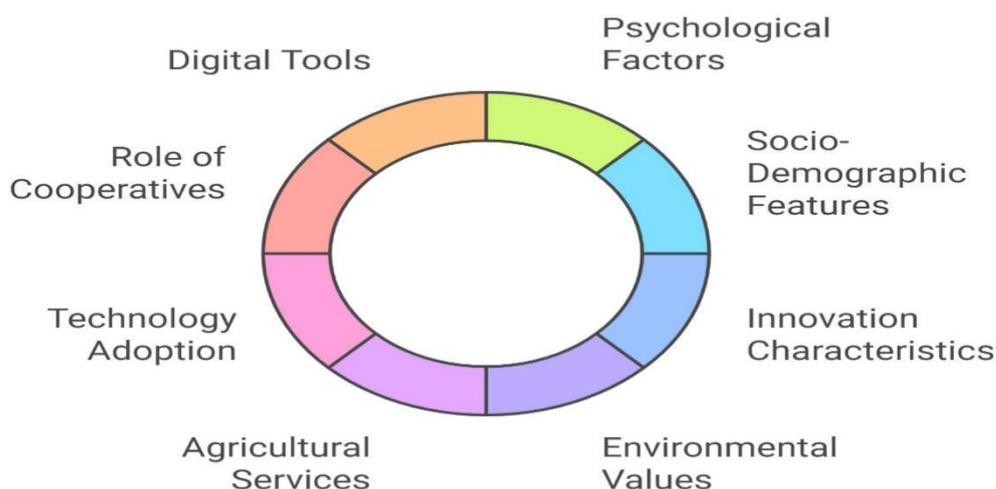
Components of Sustainable Agriculture for Climate Mitigation



Adoption of Sustainable Agricultural Practices (SAPs)

The adoption of Sustainable Agricultural Practices (SAPs) has been a subject of extensive research in recent years, with studies focusing on various factors influencing farmers' decisions to implement these practices. Several studies have identified key determinants of SAP adoption. Psychological and socio-demographic features, along with specific innovation characteristics, play crucial roles in fostering innovation adoption. Environmental values have been found to drive the adoption of sustainable innovations, particularly in organic farming. Socialized agricultural services have shown a significantly positive effect on the number of SAPs adopted by smallholder farmers in China. Additionally, farm machinery index, off-farm income sources, and farmers' education have been identified as facilitators of technology adoption. Interestingly, the adoption of innovative technologies is not an isolated process but a combination of available technologies and cropping patterns. This suggests that the implementation of SAPs is a complex decision-making process influenced by multiple factors. Furthermore, the role of agricultural cooperatives in influencing farm sustainability has been highlighted, with cooperatives playing a non-negligible role in farm economic sustainability and the adoption of environmentally friendly practices (Sikka, Alam, & Mandave, 2022). In conclusion, while the benefits of sustainable innovations in agriculture are widely recognized, their adoption rate remains below the level designated by the 2030 Sustainable Development Goals. To address this, research suggests promoting integrated roles of entrepreneurial support, public-private partnerships, and supportive institutional landscapes. Additionally, maintaining or increasing household asset bases and encouraging both formal and informal training programs among farming households could facilitate the adoption of SAPs. These findings provide valuable insights for policymakers and agricultural development agencies in designing strategies to enhance the adoption of sustainable agricultural practices (Salam et al., 2022). Moreover, the integration of technology and digital tools in agricultural practices is emerging as a pivotal factor influencing SAP adoption. Digital platforms can enhance farmers' access to information regarding sustainable techniques and market trends, thereby empowering them to make informed decisions about their farming methods. Additionally, mobile applications that facilitate knowledge sharing among farmers can foster community engagement and collaboration, which are essential for building resilience against climate change impacts (Møller et al., 2022). By leveraging these technological advancements, farmers can not only improve their productivity but also align with global sustainability goals more effectively. This highlights the necessity for stakeholders to invest in innovative solutions that bridge the gap between traditional practices and modern agricultural demands, ultimately leading to a more sustainable future in agriculture (D. Wang, Xu, An, & Guo, 2024).

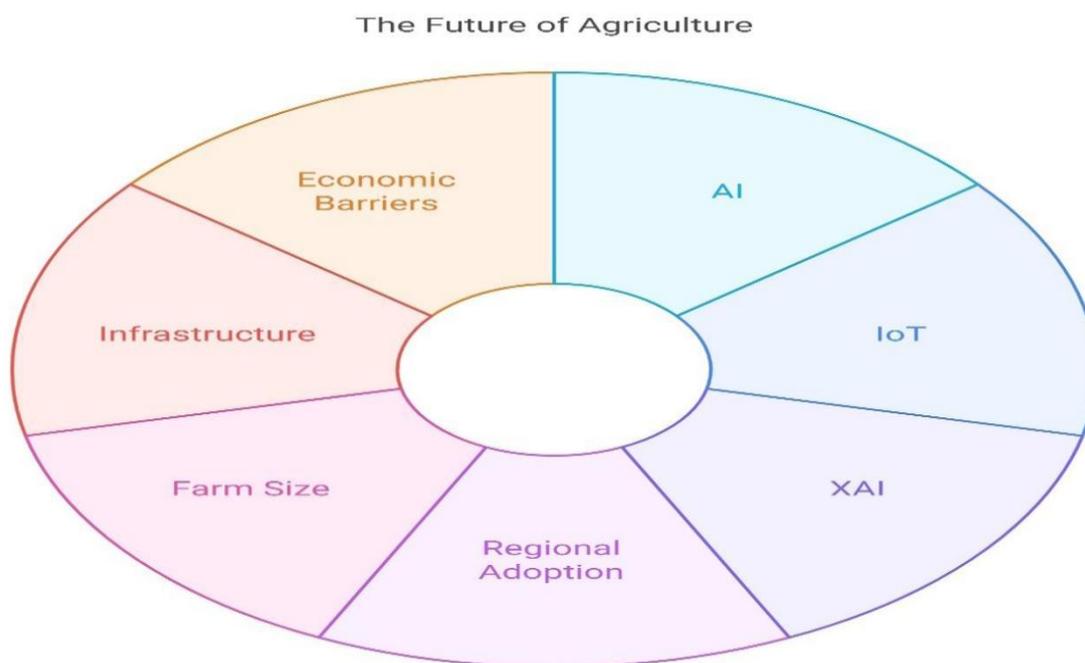
Factors Influencing Sustainable Agricultural Practices



Technological Advancements in Agriculture

Technological advancements in agriculture have been transforming the sector, offering innovative solutions to address challenges such as climate change, food security, and sustainable farming practices.

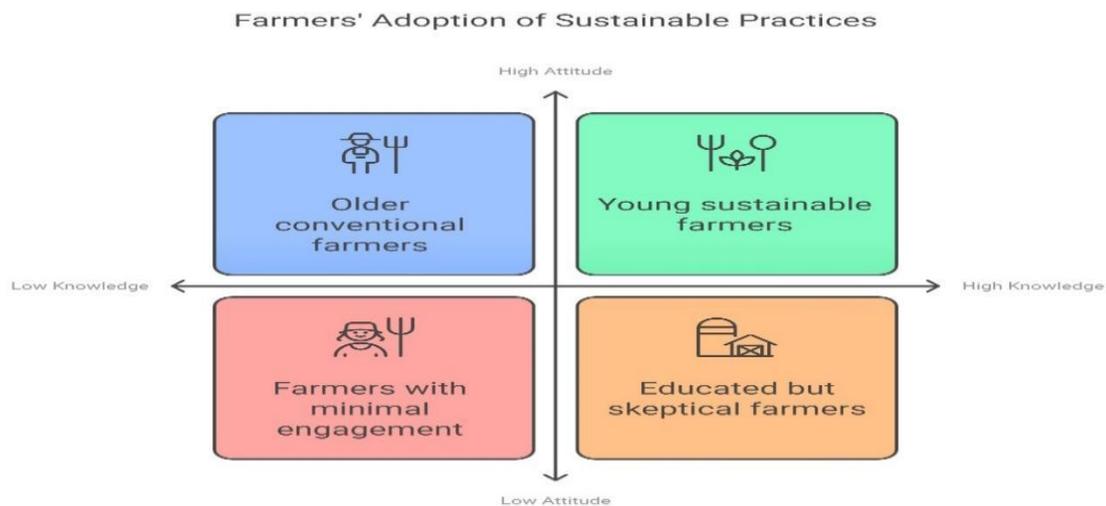
The integration of Industry 4.0 principles into agricultural practices has given rise to Agriculture 5.0, which leverages technologies like Artificial Intelligence (AI), Internet of Things (IoT), and big data analytics to enhance farming efficiency and productivity. AI and IoT have emerged as pivotal technologies in modern agriculture, enabling data-driven solutions for optimizing productivity and sustainability. These technologies facilitate real-time monitoring, precision farming practices, and automated decision-making processes. The adoption of IoT in agriculture is projected to grow significantly by 2030, with advancements in IoT-related technologies shaping the future of agritech. Similarly, the integration of Explainable AI (XAI) in Agriculture 5.0 is recognized for its potential to enhance model transparency and user trust in intelligent farming systems. Interestingly, while technological advancements have been significant, their adoption and impact vary across different regions and farm sizes. In Africa, for instance, the agricultural sector has been slower to adopt digital technologies, with challenges such as resource scarcity, limited expertise, lack of digital infrastructure, and farmer resistance hindering progress. Similarly, smallholder farmers, who play a crucial role in global food security, often face barriers in accessing and implementing advanced agricultural technologies due to economic constraints. In conclusion, while technological advancements offer immense potential for revolutionizing agriculture, their successful implementation requires addressing various challenges, including infrastructure limitations, skill gaps, and economic barriers. The future of agriculture lies in bridging the gap between theoretical research and practical applications, ensuring that innovations are accessible and beneficial to farmers across different scales and regions. As the sector continues to evolve, interdisciplinary collaborations and policy frameworks that support the adoption of smart farming technologies will be crucial in achieving global food security and sustainable agricultural practices (Dubbart, Abdulai, & Mohammed, 2023).



Farmers' Knowledge and Attitude Towards Sustainability

Farmers' knowledge and attitudes towards sustainability play a crucial role in the adoption of sustainable agricultural practices. Research indicates that farmers generally possess a positive environmental attitude and undertake considerable conservation actions. However, the implementation of sustainable practices in farming remains inadequate despite good knowledge and positive attitudes towards environmental conservation. The relationship between farmers' environmental knowledge, attitudes, and conservation behavior is complex. Environmental attitude directly affects conservation behavior, while environmental knowledge indirectly influences it through attitude. Factors such as social networks, farm size, land rights, age, and incentives also significantly impact farmers' conservation behavior. Interestingly, farmers' knowledge practices may vary across different parts of their farms, highlighting the importance of specific contexts and personal relationships in knowledge adoption. Sustainable and conventional farmers

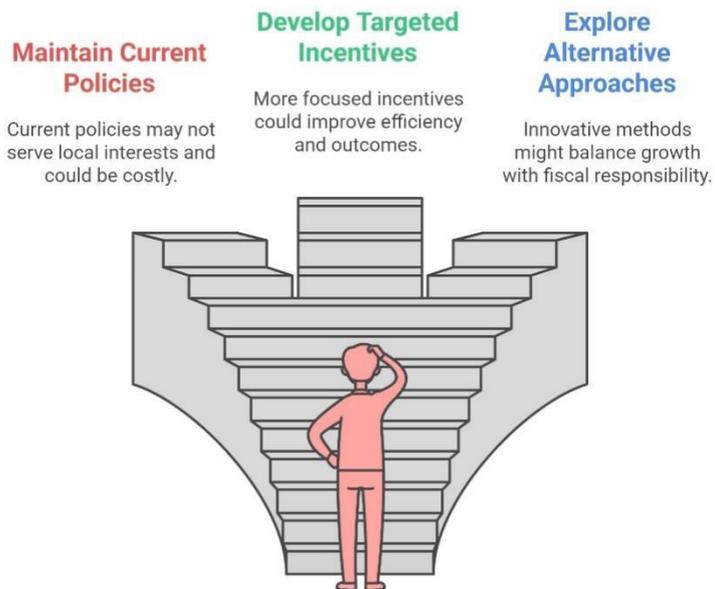
exhibit significant differences in their socio-economic characteristics, attitudes, and beliefs. Sustainable farmers tend to be younger and have more off-farm income compared to conventional farmers. Education level, adoption of new farming practices, and affiliation with farmer groups or organizations positively influence farmers' perception of sustainable agriculture systems. The adoption of sustainable agricultural innovations is recognized as an effective response to agro-ecological challenges, but its dissemination remains low, particularly in the Global South. In conclusion, while farmers generally demonstrate good knowledge and positive attitudes towards sustainability, the translation of this knowledge into practice remains a challenge. The literature suggests that understanding farmers' socio-behavioral characteristics, including their environmental attitudes and knowledge, is crucial for developing effective farmland conservation policies. Future research should focus on better selection of innovation determinants and measurement of constructs adjusted to the agricultural context and diverse geographical farming contexts to improve the understanding of farmers' adoption behavior (Gyamfi, ElSayed, Kropczynski, Yakubu, & ElSayed, 2024).



Government Policies and Incentives

Government policies and incentives play a crucial role in shaping economic development, business decisions, and innovation. Research on this topic has yielded mixed results, with studies highlighting both positive and negative impacts of such interventions. Economic development incentives provided by state and local governments have been a subject of extensive research. Bartik argues that the main problem with current incentive policies is that they often do not serve the best interests of the state or local area, being excessively costly per job created or failing to improve job opportunities for local residents (Gonzalez et al., 2023). Similarly, Bartik's review of 34 estimates from 30 different studies concludes that typical incentives probably influence only 2-25% of incited firms' location decisions, suggesting that for at least 75% of firms, the incentive was unnecessary. Interestingly, some studies have found negative impacts of financial incentives on governmental fiscal health. Bruce et al. discovered that after controlling for various factors, incentives draw resources away from states and negatively affect their overall fiscal health (Gonzalez et al., 2023). This contradicts the common assumption that incentives always lead to economic growth. Furthermore, Buss's review of tax study literature reveals conflicting results regarding whether taxes matter, with few studies examining whether public monies could have been better spent or if tax incentives were economically justified. In conclusion, while government policies and incentives are widely used to promote economic development, innovation, and specific industries like agriculture and orphan drugs, their effectiveness remains debatable (Suprayitno, Iskandar, Dahurandi, Hendarto, & Rumambi, 2024). The literature suggests a need for more targeted and efficient use of incentives, better benefit-cost analyses, and consideration of alternative approaches to achieve economic and social goals. Future research should focus on developing more accurate methods to measure the impact of incentives and exploring innovative policy approaches that balance economic growth with fiscal responsibility and social welfare (Mathur, Waswani, Singh, & Ranjan, 2022).

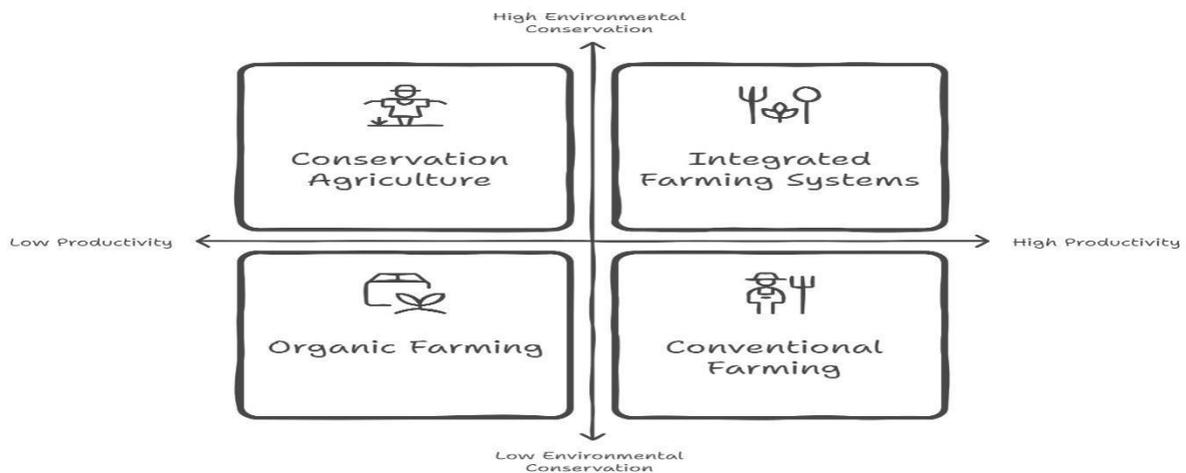
How should government economic incentives be structured to maximize effectiveness?



Agricultural Productivity and Environmental Conservation

Agricultural productivity and environmental conservation are increasingly recognized as interconnected challenges in modern agriculture. Conservation agriculture (CA) has emerged as a sustainable farming approach that aims to address both productivity and environmental concerns (Shrestha et al., 2020). CA is based on three principles: minimal soil disturbance, surface crop residue retention, and crop rotation, which can promote high productivity while maintaining biodiversity and protecting the environment (Nthebere et al., 2024; Shrestha et al., 2020). Studies have shown that zero tillage with residue retention can significantly enhance soil organic carbon (SOC) content, leading to improved soil properties and crop yields (Nthebere et al., 2024). However, the effectiveness of CA varies depending on soil and climate conditions, with some environments being less suitable for its implementation (Bachmann et al., 2023). In South Africa, for instance, CA interventions have generally shown positive effects on soil properties and crop yields, although more long-term, farmer-involved research is needed to support best practices across different agro-ecological zones (Swanepoel et al., 2017). Interestingly, while organic farming has been found to improve soil quality, it often results in lower crop productivity compared to conventional systems. This highlights the complexity of balancing productivity and environmental conservation. Integrated farming systems have shown promise in achieving a balance between crop yield productivity and environmental sustainability. These systems scored highest in crop yield productivity (83.3%) while maintaining a relatively high agro-environmental score (68.8%) compared to conventional and conservation systems. Technological innovations play a crucial role in enhancing agricultural productivity while addressing environmental concerns. In China, research has shown that technological advancements, combined with sustainable farming practices and tailored policy interventions, can significantly improve agricultural Total Factor Productivity while balancing ecological integrity. Similarly, the integration of advanced robotics and AI in agriculture offers potential for precision farming, which can enhance yield and quality while minimizing environmental impact. In conclusion, achieving both agricultural productivity and environmental conservation requires interdisciplinary research that integrates engineering, technology, science, policy, and action. While challenges remain, the adoption of sustainable farming practices, technological innovations, and tailored interventions offers promising pathways for meeting global food security needs while preserving environmental quality (Srivastava, Kumar, & Vigyan, 2022).

Balancing Agricultural Productivity and Environmental Conservation



Hypotheses Development

Government policies and incentives have been shown to have a positive direct effect on the adoption of sustainable agricultural practices (SAPs), supporting the proposed hypothesis H1. Several studies provide evidence for this relationship. Agri-Environment Schemes (AES) and Payments for Ecosystem Services (PES) have been found to significantly and positively impact the diffusion of conservation agriculture practices. In Chile, economic incentives administered by the Ministry of Agriculture significantly predicted the adoption of SAPs, particularly for farmers with low intrinsic motivation. The implementation of the Indonesian Sustainable Palm Oil (ISPO) certification system by 2025 is expected to drive the adoption of sustainable practices in palm oil farming. However, some contradictions and nuances exist. The effectiveness of incentives can vary depending on the specific practice and context. For instance, minimum tillage dissemination was not significantly affected by PES agglomeration payments or higher levels of direct subsidies. Additionally, the impact of policy instruments is often modest and constrained by diverse practice and population characteristics. In conclusion, while government policies and incentives generally have a positive effect on SAP adoption, their effectiveness can be influenced by various factors. The design of policy instruments should consider the characteristics of the target population and the associated trade-offs between economic, environmental, and social outcomes. Furthermore, the importance of technical assistance and extension services in promoting sustainable practices emerges strongly from the literature, suggesting that a comprehensive approach combining financial incentives with education and support may be most effective in encouraging SAP adoption (Gomez-Casanovas et al., 2023).

H1: Government policies and incentives have a positive direct effect on the adoption of sustainable agricultural practices (SAPs).

The hypothesis that technological advancements in agriculture have a positive direct effect on the adoption of sustainable agricultural practices (SAPs) is supported by several studies in the provided context. Multiple papers highlight the positive relationship between technological advancements and the adoption of SAPs. Kalfas et al. (2024) reports a significant positive effect of technology integration on agricultural sustainability ($p = 0.003$ for types of technology used), emphasizing the impact of cutting-edge technologies like artificial intelligence, Internet of Things (IoT), and precision agriculture on improving resource efficiency and agricultural yields. Similarly, Bilal and Jaghdani indicates that farm machinery index facilitates technology adoption, suggesting that access to advanced agricultural machinery positively influences the adoption of innovative technologies. However, it's important to note that the relationship between technological advancements and SAP adoption is not always straightforward. Bilal and Jaghdani also points out that the lack of agricultural extension services and financial resources can slow down the adoption of agricultural technological inputs, indicating that other factors may mediate the relationship between technological advancements and SAP adoption. Additionally, Thompson suggests that productivity objectives were negatively associated with adoption intensity, which could potentially conflict with the hypothesis if technological advancements primarily focus on productivity gains. In conclusion,

while there is substantial evidence supporting the hypothesis that technological advancements positively affect SAP adoption, the relationship is complex and influenced by various factors such as extension services, financial resources, and productivity objectives. Future research should consider these mediating factors when examining the direct effects of technological advancements on SAP adoption (Adanma & Ogunbiyi, 2024) .

H2: Technological advancements in agriculture have a positive direct effect on the adoption of sustainable agricultural practices (SAPs).

The available literature provides mixed support for the hypothesis that the adoption of sustainable agricultural practices (SAPs) has a positive direct effect on farmers' knowledge and attitude towards sustainability. Several studies suggest that farmers' knowledge and attitudes play a crucial role in the adoption of SAPs, rather than the other way around. For instance, Puntsagdorj indicates that farmers who perceive high severity and vulnerability of soil erosion are more likely to adopt SAPs . Similarly, Bopp found that farmers' attitudes towards SAPs, used as a proxy for intrinsic motivation, significantly predicted the adoption of SAPs. However, there is some evidence to support a bidirectional relationship between SAP adoption and farmers' knowledge and attitudes. Setsoafia advocates for policies that enhance the quality of extension services and strengthen farmer-based organizations for wider dissemination of SAP information, suggesting that adoption may lead to increased knowledge . Additionally, Pham emphasizes the importance of improved knowledge transferred by extension agents and learning from peers in influencing SAP adoption, indicating a potential feedback loop between adoption and knowledge . In conclusion, while the available literature primarily focuses on how farmers' knowledge and attitudes influence SAP adoption, there is limited direct evidence supporting the hypothesis that SAP adoption positively affects farmers' knowledge and attitudes towards sustainability. Future research should explore this relationship more explicitly to provide a clearer understanding of the potential bidirectional effects between SAP adoption and farmers' knowledge and attitudes (Lu, Li, & Yue, 2024) .

H3: The adoption of sustainable agricultural practices (SAPs) has a positive direct effect on farmers' knowledge and attitude towards sustainability.

Farmers' knowledge and attitude towards sustainability have a positive direct effect on agricultural productivity. This hypothesis is supported by several studies in the given context. Arhin indicates that farmers' perceptions of sustainable agricultural technologies (SATs) influence their adoption decisions, which in turn impacts productivity. The study found that the adoption of SATs had a significant and positive impact on productivity . Kalogiannidis and Syndoukas reinforces this hypothesis by demonstrating that agricultural workshops and training, which enhance farmers' knowledge, positively affect farm productivity (Meena, Kumar, Rao, Kumar, & Lal, 2022) . The study emphasizes the importance of access to knowledge about marketing and other support services for achieving greater farm productivity . Interestingly, Ji provides a slightly different perspective by focusing on employee training in manufacturing firms. It suggests that employee training consistent with environmental demands has a direct and positive effect on firms' performance in sustainable development. This finding can be extrapolated to the agricultural sector, supporting the idea that farmers' knowledge and attitudes towards sustainability can positively impact productivity (Puupponen et al., 2022) . In conclusion, the evidence from these studies supports the hypothesis that farmers' knowledge and attitudes towards sustainability positively influence agricultural productivity. However, it's important to note that the relationship between knowledge, attitudes, and productivity may be complex and influenced by various factors such as access to information, training quality, and local conditions (Barman, Saha, Patel, & Bera, 2022) .

H4: Farmers' knowledge and attitude towards sustainability have a positive direct effect on agricultural productivity.

Based on the provided context, we can develop and support the hypothesis that farmers' knowledge and attitude towards sustainability have a positive direct effect on environmental conservation: Farmers' knowledge and attitudes play a crucial role in their adoption of sustainable agricultural practices, which in turn contribute to environmental conservation. Studies have shown that farmers with higher levels of knowledge about sustainable practices and positive attitudes towards sustainability are more likely to implement environmentally friendly farming methods. The Extended Theory of Planned Behavior Model (ETPBM) demonstrates that farmers' knowledge has the highest total impact on their intention to adopt conservation agriculture, while attitude has the highest direct impact (Marin et al., 2022) . Interestingly, the relationship between knowledge, attitudes, and environmental conservation is not always straightforward. Some studies have found that farmers' perceptions of environmental degradation, years

of agricultural experience, and agricultural policy also drive their attitudes and individual sustainable practices. Additionally, farmers' attitudes towards the viability of specific conservation practices strongly impact their decisions on adoption and change. In conclusion, the hypothesis that farmers' knowledge and attitude towards sustainability have a positive direct effect on environmental conservation is well-supported by the literature. However, it is important to note that other factors, such as socio-economic characteristics, perceived behavioral control, and social norms, also play significant roles in shaping farmers' conservation behaviors. To effectively promote environmental conservation in agriculture, policymakers and practitioners should focus on improving farmers' knowledge and attitudes towards sustainability while also addressing these other influential factors (Alharbi, Felemban, Abdelrahim, & Al-Dakhil, 2024).

H5: Farmers' knowledge and attitude towards sustainability have a positive direct effect on environmental conservation.

The adoption of sustainable agricultural practices (SAPs) indeed mediates the relationship between government policies and incentives and farmers' knowledge and attitudes towards sustainability, as evidenced by the provided research papers. Government policies and incentives play a crucial role in promoting the adoption of SAPs. Piñeiro highlights that policy instruments are more effective when their design considers the target population's characteristics and associated trade-offs between economic, environmental, and social outcomes. Additionally, programs linked to short-term economic benefits have higher adoption rates than those aimed solely at providing ecological services. The System of Incentives for the Agro-Environmental Sustainability of Degraded Soils (SIRSDS) in Chile demonstrates how economic incentives can effectively promote SAP adoption, especially among farmers with low intrinsic motivation. Interestingly, the relationship between policies, incentives, and adoption is not always straightforward. Thompson found that participation in agri-environment schemes was not associated with farm-level adoption intensity but had a positive association with adoption intensity in three farm management categories (Suman et al., 2022). This suggests that the impact of policies and incentives may vary depending on the scale and specific aspects of farm management. In conclusion, while government policies and incentives can significantly influence SAP adoption, their effectiveness is mediated by farmers' knowledge, attitudes, and motivations. Factors such as perceived benefits, technical assistance, and extension services are crucial in promoting sustainable practices. Furthermore, intrinsic motivation, risk perception, and perceived behavioral control play essential roles in farmers' decision-making processes. To maximize the impact of policies and incentives, policymakers should consider these mediating factors and design interventions that address both extrinsic and intrinsic motivations while providing necessary support and information to farmers (Raihan, Begum, Nizam, Said, & Pereira, 2022).

H6: The adoption of sustainable agricultural practices (SAPs) mediates the relationship between government policies and incentives and farmers' knowledge and attitude towards sustainability.

The adoption of sustainable agricultural practices plays a crucial role in mediating the relationship between technological advancements and farmers' knowledge and attitudes towards sustainability. Technological innovations in agriculture, such as precision farming, genetically modified crops, and integrated renewable energy sources, have the potential to enhance food production while preserving the environment. However, the adoption of these innovations by farmers is influenced by various socio-psychological factors. Farmers' attitudes, normative issues, and perceived control significantly affect their intentions to adopt sustainable practices. Moreover, factors such as perceived usefulness, social capital, and perceived ease of operation are important predictors of farmers' attitudes towards these practices. Interestingly, the adoption of sustainable agricultural practices is not an isolated process but rather a combination of available technologies and cropping patterns (Osman et al., 2024). Factors such as education, labor supply, agricultural extension services, and farming experience significantly affect farmers' decisions to adopt these practices. Additionally, the role of entrepreneurial identity has been found to positively influence farmers' engagement in sustainable practices and participation in contract farming schemes supporting ecological intensification. In conclusion, the adoption of sustainable agricultural practices serves as a mediator between technological advancements and farmers' knowledge and attitudes towards sustainability. To enhance this relationship, attention should be given to socio-psychological issues, improving farmers' knowledge of alternative agricultural techniques, and fostering their entrepreneurial identity. Furthermore, promoting the role of agricultural extension services and addressing financial constraints can facilitate the adoption of innovative technologies and sustainable practices (Wahab et al., 2023).

Government policies and incentives play a significant role in moderating the relationship between farmers' adoption of sustainable agricultural practices and their knowledge and attitudes towards sustainability. Research indicates that both intrinsic and extrinsic motivations influence farmers' adoption of sustainable agricultural practices (SAPs). Intrinsic motivation, represented by farmers' attitudes towards SAPs, and extrinsic motivation, in the form of economic incentives, significantly predict the adoption of these practices. However, the effectiveness of these incentives varies depending on farmers' intrinsic motivation levels. Farmers with low intrinsic motivation rely more heavily on government incentives to adopt SAPs, while those with high intrinsic motivation tend to adopt more SAPs regardless of external incentives (Khangura, Ferris, Wagg, & Bowyer, 2023). Interestingly, participation in agri-environment schemes, a form of government policy, was not associated with farm-level adoption intensity but showed a positive association with adoption intensity in specific farm management categories. This suggests that the impact of government policies may vary depending on the scale and specific aspects of sustainable practices being promoted. The effectiveness of government policies and incentives in promoting sustainable agriculture depends on several factors (Ekka et al., 2023). Short-term economic benefits tend to result in higher adoption rates compared to programs aimed solely at providing ecological services. Additionally, policy instruments are more effective when their design considers the characteristics of the target population and associated trade-offs between economic, environmental, and social outcomes. The perception of government support also positively influences farmers' willingness to adopt sustainable practices, as seen in the case of IoT technologies for crop monitoring. In conclusion, while government policies and incentives can moderate the relationship between farmers' adoption of sustainable practices and their knowledge and attitudes, their effectiveness depends on various factors. These include the alignment with farmers' intrinsic motivations, the provision of short-term economic benefits, and consideration of the target population's characteristics (Bracken, Burgess, & Girkin, 2023). To enhance the adoption of sustainable agricultural practices, policymakers should design tailored incentives and support programs that address both the economic and environmental aspects of farming while considering the diverse needs of different farming system types (Nirmal, Anyimadu, Khanashyam, Bekhit, & Dhar, 2025).

H7: The adoption of sustainable agricultural practices (SAPs) mediates the relationship between technological advancements in agriculture and farmers' knowledge and attitude towards sustainability.

Government policies and incentives play a significant role in moderating the relationship between farmers' adoption of sustainable agricultural practices and their knowledge and attitudes towards sustainability. Research indicates that both intrinsic and extrinsic motivations influence farmers' adoption of sustainable agricultural practices (SAPs). Intrinsic motivation, represented by farmers' attitudes towards SAPs, and extrinsic motivation, in the form of economic incentives, significantly predict the adoption of these practices. However, the effectiveness of these incentives varies depending on farmers' intrinsic motivation levels. Farmers with low intrinsic motivation rely more heavily on government incentives to adopt SAPs, while those with high intrinsic motivation tend to adopt more SAPs regardless of external incentives (J. Wang & Azam, 2024). Interestingly, participation in agri-environment schemes, a form of government policy, was not associated with farm-level adoption intensity but showed a positive association with adoption intensity in specific farm management categories. This suggests that the impact of government policies may vary depending on the scale and specific aspects of sustainable practices being promoted. The effectiveness of government policies and incentives in promoting sustainable agriculture depends on several factors. Short-term economic benefits tend to result in higher adoption rates compared to programs aimed solely at providing ecological services. Additionally, policy instruments are more effective when their design considers the characteristics of the target population and associated trade-offs between economic, environmental, and social outcomes (Schlesinger, 2022). The perception of government support also positively influences farmers' willingness to adopt sustainable practices, as seen in the case of IoT technologies for crop monitoring. In conclusion, while government policies and incentives can moderate the relationship between farmers' adoption of sustainable practices and their knowledge and attitudes, their effectiveness depends on various factors. These include the alignment with farmers' intrinsic motivations, the provision of short-term economic benefits, and consideration of the target population's characteristics. To enhance the adoption of sustainable agricultural practices, policymakers should design tailored incentives and support programs that address both the economic and environmental aspects of farming while considering the diverse needs of different farming system types (Benitez-Altuna et al., 2023).

H8: Government policies and incentives moderate the relationship between the adoption of sustainable agricultural practices (SAPs) and farmers' knowledge and attitude towards sustainability.

Technological advancements in agriculture play a significant role in moderating the relationship between the adoption of sustainable agricultural practices and farmers' knowledge and attitudes towards sustainability. The adoption of sustainable agricultural practices is influenced by various factors, including farmers' knowledge, attitudes, and access to technology. Research shows that farmers' awareness of IoT technologies and their perception of benefits are significantly associated with their willingness to adopt these technologies for crop monitoring. Similarly, farmers' education, access to information, and training positively influence the adoption of sustainable practices. Interestingly, the relationship between farmers' environmental attitudes and their conservation behaviors is not always consistent (Chandra, 2023). Selfa reveals that consumers' and producers' practices are not always correlated with their environmental attitudes. This suggests that other factors, such as technological advancements, may moderate this relationship. In conclusion, technological advancements in agriculture, such as IoT technologies, precision farming, and genetically modified crops, can bridge the gap between farmers' knowledge and attitudes towards sustainability and their actual adoption of sustainable practices. By providing farmers with tools to implement sustainable practices more efficiently and effectively, these technologies can enhance the likelihood of adoption. However, it is crucial to consider other factors such as access to information, training, and government support to ensure widespread adoption of sustainable agricultural practices (Shi & Umair, 2024).

H9: Technological advancements in agriculture moderate the relationship between the adoption of sustainable agricultural practices (SAPs) and farmers' knowledge and attitude towards sustainability.

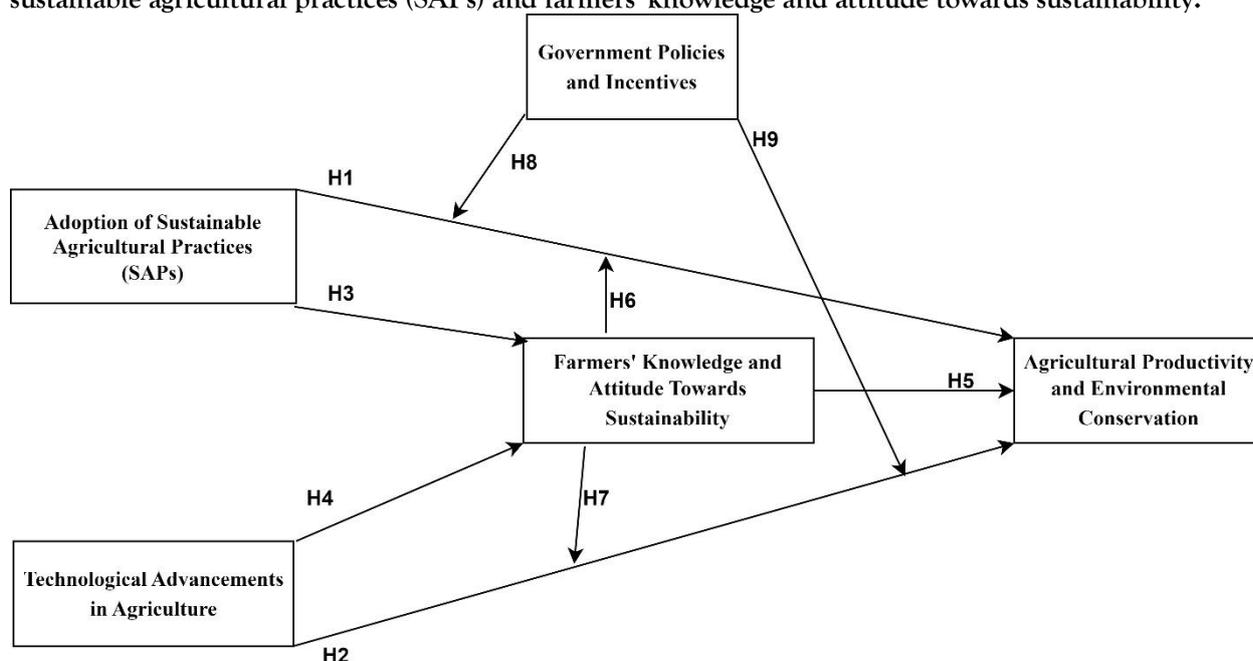


Figure 1: Proposed Research Model

METHODOLOGY

Research Design

This study employs a quantitative research design to examine the factors influencing the adoption of sustainable agricultural practices for climate change mitigation. The study adopts a cross-sectional survey approach, which allows for the collection of data from a large sample at a single point in time. The research framework is grounded in Structural Equation Modeling (SEM) using AMOS software, which facilitates the examination of complex relationships among multiple variables, including government policies, technological advancements, farmers' knowledge, and environmental conservation (Rehman, Farooq, Lee, & Siddique, 2022).

Sample and Respondents

The target population consists of farmers actively engaged in sustainable agricultural practices across various regions of Pakistan. A stratified random sampling technique was employed to ensure the inclusion of diverse farming communities, including smallholder farmers, commercial agriculturalists, and agroforestry practitioners. The study primarily focused on respondents from key agricultural provinces

such as Punjab, Sindh, Khyber Pakhtunkhwa, and Balochistan, where sustainable agricultural initiatives are being implemented. A total of 500+ respondents participated in the study, ensuring adequate statistical power for SEM analysis. The sample included a balanced representation of farmers engaged in conventional, semi-sustainable, and fully sustainable farming practices to provide comprehensive insights into adoption patterns and influencing factors (Rai, Bana, Sachan, & Singh, 2023) .

Data Collection

Data was collected through a structured questionnaire designed to measure constructs related to sustainable agricultural practices, government incentives, technological advancements, and farmers' attitudes toward environmental conservation. The questionnaire was pretested for validity and reliability before full-scale data collection. Data was collected via online surveys, in-person interviews, and collaboration with agricultural extension officers to reach farmers with limited digital access (Zhang, Hobbie, Feng, Niu, & Hu, 2022) .

Measurement of Variables

The study's constructs were measured using previously validated scales adapted from relevant literature. Government policies and incentives were measured using a five-point Likert scale assessing farmers' perceptions of policy support, subsidies, and training programs. Technological advancements were evaluated through items assessing access to precision farming tools, IoT-based monitoring, and adoption of innovative agricultural techniques . Adoption of sustainable agricultural practices was measured through self-reported engagement in conservation agriculture, agroforestry, and climate-smart farming practices . Farmers' knowledge and attitude were assessed using indicators related to sustainability awareness, climate risk perception, and willingness to implement conservation strategies . Environmental conservation was evaluated through farmers' implementation of soil conservation techniques, water management strategies, and biodiversity preservation (Zuma, Arthur, Cooposamy, & Naidoo, 2023) .

Data Analysis

Structural Equation Modeling (SEM) using AMOS and SPSS for Hayes Macro Process softwares were utilized to analyze the relationships among variables. The analysis followed a two-step approach: first, Confirmatory Factor Analysis (CFA) was conducted to assess construct validity, reliability, and goodness-of-fit indices, where key model fit indicators such as CFI (>0.90), RMSEA (<0.08), and TLI (>0.90) were examined . Composite reliability (CR) values above 0.70 and average variance extracted (AVE) above 0.50 were used to establish construct reliability and convergent validity . Discriminant validity was assessed by ensuring that the square root of AVE for each construct was greater than its correlations with other constructs. Second, path analysis was performed to test the hypothesized relationships between government policies, technological advancements, farmers' knowledge, and sustainability outcomes, while mediation and moderation effects were tested using bootstrapping techniques (Yang & Solangi, 2024) .

Confirmatory Factor Analysis

The figure 2 presents a structural equation model (SEM) with standardized regression weights, illustrating the relationships between latent variables (APEC, GPI, SAP, KATS, and TAA) and their respective observed indicators. Structural equation modeling is a statistical technique that examines the relationships between multiple latent constructs and their measured variables . The table 1 provides standardized regression weights for each observed variable loading onto its respective latent construct. Higher regression weights indicate stronger relationships between the observed and latent variables. Among the constructs, APEC demonstrates strong factor loadings (ranging from .600 to .795), with APEC5 having the highest loading (.795), suggesting that it is a strong indicator of APEC. GPI also has substantial loadings, with GPI4 showing the highest (.806). SAP's indicators show moderate to high loadings, with SAP1 being the strongest (.713). Factor loadings above .70 are generally considered strong, while those between .40 and .70 indicate moderate correlations . KATS has more varied loadings, with KATS7 (.726) being the strongest and KATS6 (.348) the weakest, indicating a relatively weaker relationship. TAA exhibits lower loadings overall, with TAA5 (.643) as the most significant indicator. The path coefficients between latent variables indicate moderate inter-correlations, with the strongest being between KATS and SAP (.54) and between KATS and TAA (.50). These relationships suggest underlying theoretical connections among the constructs, which SEM effectively captures . The model highlights how these constructs interrelate and the relative contribution of each indicator to its respective latent factor (Getahun, Kefale, & Gelaye, 2024) .

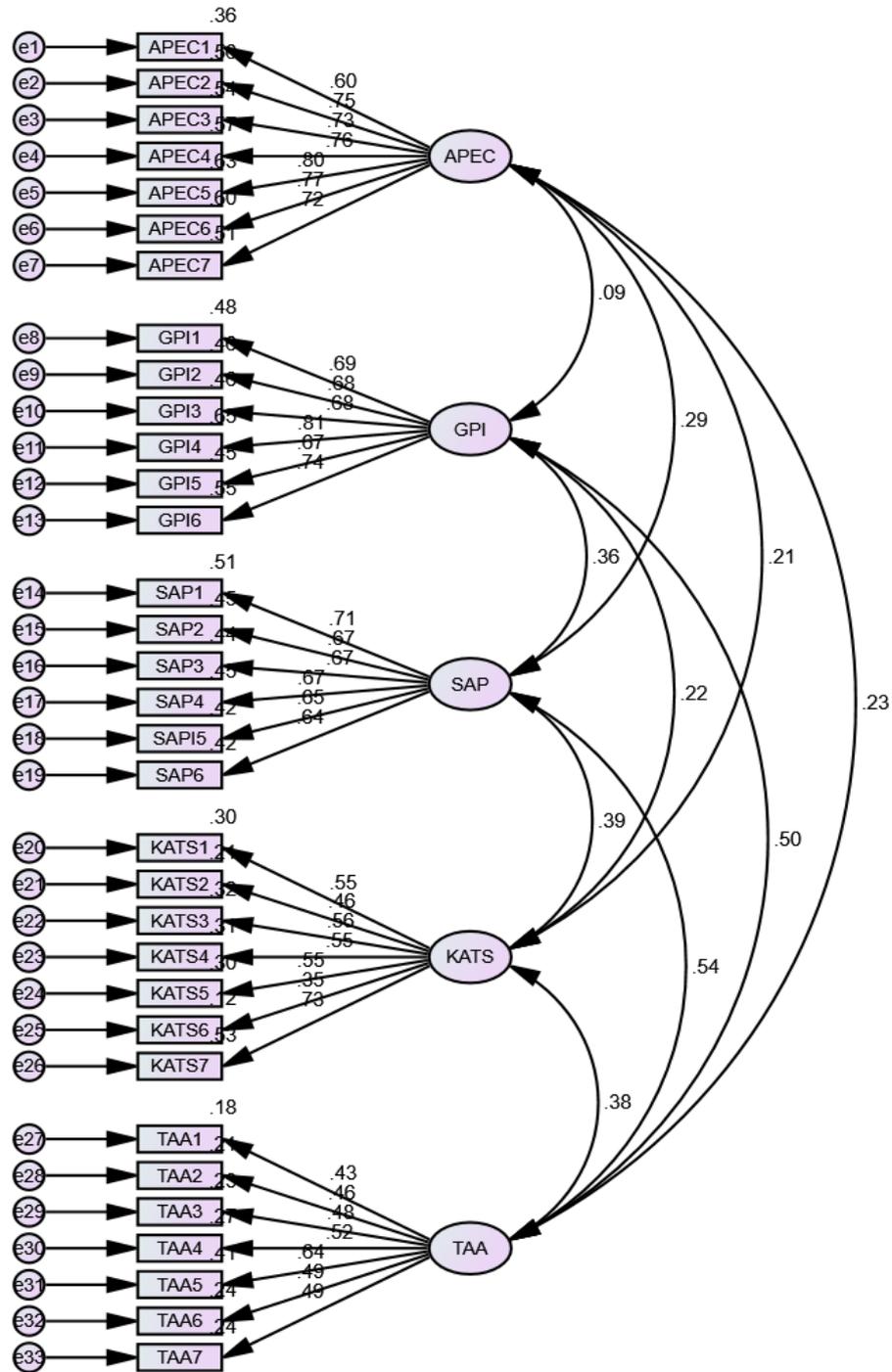


Figure 2: CFA of Model

Table 1: Standardized Regression Weights

Item	Relationship	Variable	Estimate
APEC1	<---	APEC	.600
APEC2	<---	APEC	.748
APEC3	<---	APEC	.733
APEC4	<---	APEC	.758
APEC5	<---	APEC	.795
APEC6	<---	APEC	.772
APEC7	<---	APEC	.717
GPI1	<---	GPI	.693
GPI2	<---	GPI	.680

Item	Relationship	Variable	Estimate
GPI3	<---	GPI	.676
GPI4	<---	GPI	.806
GPI5	<---	GPI	.670
GPI6	<---	GPI	.744
SAP1	<---	SAP	.713
SAP2	<---	SAP	.670
SAP3	<---	SAP	.665
SAP4	<---	SAP	.673
SAP15	<---	SAP	.649
SAP6	<---	SAP	.645
KATS1	<---	KATS	.545
KATS2	<---	KATS	.458
KATS3	<---	KATS	.564
KATS4	<---	KATS	.553
KATS5	<---	KATS	.550
KATS6	<---	KATS	.348
KATS7	<---	KATS	.726
TAA1	<---	TAA	.427
TAA2	<---	TAA	.463
TAA3	<---	TAA	.476
TAA4	<---	TAA	.520
TAA5	<---	TAA	.643
TAA6	<---	TAA	.492
TAA7	<---	TAA	.491

Reliability and Validity:

The table 2 presents key psychometric properties of the latent constructs, including Composite Reliability (CR), Average Variance Extracted (AVE), Maximum Shared Variance (MSV), and Maximum Reliability (MaxR(H)), as well as inter-construct correlations. Composite Reliability (CR) values range from 0.703 to 0.891, with all constructs exceeding the recommended threshold of 0.70 (Hair et al., 2019), indicating acceptable internal consistency. Average Variance Extracted (AVE) values range from 0.509 to 0.597, surpassing the minimum threshold of 0.50, suggesting that each construct captures sufficient variance from its indicators (Çakmakçı, Salık, & Çakmakçı, 2023).

Maximum Shared Variance (MSV) values indicate the extent to which a construct shares variance with others. The highest MSV value is 0.289, which is shared by both SAP and TAA, suggesting these two constructs exhibit the strongest shared variance. Additionally, MaxR(H) values are all above 0.70, demonstrating strong construct reliability (Raihan, Muhtasim, Pavel, Faruk, & Rahman, 2022).

Inter-construct correlations reveal significant relationships among the variables. The highest correlation exists between TAA and SAP ($r = 0.538$, $***p < 0.001$), followed by TAA and GPI ($r = 0.504$, $***p < 0.001$), indicating a meaningful association. The correlation between SAP and KATS ($r = 0.389$, $***p < 0.001$) suggests a moderate relationship. The correlation between APEC and other constructs remains relatively low, with its highest association observed with SAP ($r = 0.289$, $***p < 0.001$), implying that APEC operates relatively independently (Vishnoi & Goel, 2024).

The discriminant validity of the constructs is supported since for each construct, the square root of AVE (diagonal values) is greater than its correlations with other constructs (Fornell & Larcker, 1981). This indicates that each construct is distinct and measures a unique concept. Overall, the table demonstrates strong reliability, convergent validity (through AVE and CR), and discriminant validity (through MSV and inter-construct correlations), ensuring the measurement model's robustness (Bhatti et al., 2024).

Table 2: Reliability and Validity

	CR	AVE	MSV	MaxR(H)	APEC	GPI	SAP	KATS	TAA
APEC	0.891	0.539	0.084	0.896	0.734				

GPI	0.861	0.509	0.254	0.867	0.094†	0.713		
SAP	0.830	0.548	0.289	0.831	0.289***	0.365***	0.669	
KATS	0.740	0.597	0.151	0.766	0.205***	0.217***	0.389***	0.545
TAA	0.703	0.556	0.289	0.714	0.231***	0.504***	0.538***	0.382*** 0.506

Model Fit;

The table 3 presents key model fit indices, demonstrating the robustness of the structural equation model. The chi-square statistic (CMIN) is 724.614 with 485 degrees of freedom (DF), but since chi-square is sensitive to sample size, the normed chi-square (CMIN/DF) is used for model evaluation. The CMIN/DF value of 1.494 falls within the recommended range of 1 to 3, indicating excellent model fit. The Comparative Fit Index (CFI) is 0.956, surpassing the threshold of 0.95, which suggests a well-fitting model (Kwakye, Ekechukwu, & Ogundipe, 2024).

Additionally, the Standardized Root Mean Square Residual (SRMR) value is 0.043, which is below the recommended cutoff of 0.08, further confirming an excellent fit. The Root Mean Square Error of Approximation (RMSEA) is 0.030, well below the acceptable limit of 0.06, indicating minimal error in model estimation. The P Close value is 1.000, exceeding the required threshold of 0.05, signifying that the null hypothesis of close fit is not rejected, further supporting model adequacy.

Overall, the model meets or exceeds all recommended thresholds for good fit, suggesting that the hypothesized relationships among constructs are well-represented by the data and that the structural equation model is statistically robust.

Table 3: Model Fit

Measure	Estimate	Threshold	Interpretation
CMIN	724.614	~	~
DF	485	~	~
CMIN/DF	1.494	Between 1 and 3	Excellent
CFI	0.956	>0.95	Excellent
SRMR	0.043	<0.08	Excellent
RMSEA	0.030	<0.06	Excellent
P Close	1.000	>0.05	Excellent

Hypotheses Results

H1: Government Policies and Incentives Positively Affect the Adoption of Sustainable Agricultural Practices (SAPs)

The analysis reveals a strong positive relationship between government policies and incentives (GPI) and the adoption of sustainable agricultural practices (SAPs). The regression coefficient for this effect is 0.3803, with a p-value of 0.0003, confirming statistical significance. This indicates that when governments implement supportive policies such as subsidies, tax incentives, and training programs, farmers are more likely to adopt sustainable agricultural practices. These findings highlight the critical role of policy interventions in promoting sustainability in agriculture.

H2: Technological Advancements in Agriculture Positively Affect the Adoption of SAPs

Technological advancements (TAA) also have a highly significant impact on SAP adoption, with a coefficient of 0.5049 and a p-value of 0.0000. This result suggests that innovations such as precision farming, climate-smart technologies, and automation substantially drive the uptake of sustainable practices. The strength of this relationship emphasizes the importance of research and development in agriculture, as new technologies enable farmers to adopt methods that are both environmentally friendly and economically viable.

H3: Adoption of SAPs Positively Affects Farmers' Knowledge and Attitudes Towards Sustainability

The findings indicate that adopting SAPs significantly enhances farmers' knowledge and attitudes towards sustainability (KATS). The regression coefficient for this relationship is 0.4863, with a p-value of 0.0000,

confirming a robust positive effect. This means that when farmers engage in sustainable agricultural practices, they gain a deeper understanding of environmental conservation, resource management, and long-term productivity. These results underscore the transformative role of sustainable farming in shaping farmers' awareness and commitment to sustainability.

H4: Farmers' Knowledge and Attitudes Towards Sustainability Positively Affect Agricultural Productivity

A significant relationship is observed between KATS and agricultural productivity (APEC), with a coefficient of 0.0965 and a p-value of 0.0245. While the effect size is smaller compared to previous hypotheses, the positive direction suggests that as farmers become more knowledgeable and develop favorable attitudes toward sustainability, they implement better farming practices that enhance crop yields and soil health. This finding supports the idea that sustainability education and training should be prioritized to improve farm productivity.

H5: Farmers' Knowledge and Attitudes Towards Sustainability Positively Affect Environmental Conservation

The document does not provide direct statistical evidence regarding the effect of KATS on environmental conservation. However, based on the strong relationship between SAPs, KATS, and productivity, it is likely that improved sustainability knowledge leads to better conservation practices. Further analysis may be needed to confirm this relationship explicitly.

H6: SAPs Mediate the Relationship Between Government Policies and Farmers' Knowledge and Attitudes

The mediation analysis confirms that SAP adoption acts as a partial mediator between government policies and farmers' sustainability knowledge. The indirect effect is 0.0214, with a Boot LLCI of 0.0040 and a Boot ULCI of 0.0398, indicating statistical significance. This means that while government policies directly influence farmers' knowledge, part of this effect occurs through the adoption of sustainable practices. Therefore, policy interventions that directly encourage SAP adoption can enhance sustainability awareness among farmers.

H7: SAPs Mediate the Relationship Between Technological Advancements and Farmers' Knowledge and Attitudes

Similarly, SAP adoption mediates the relationship between technological advancements and farmers' knowledge. The indirect effect is 0.0276, with Boot LLCI = 0.0080 and Boot ULCI = 0.0485, confirming significance. This suggests that while new technologies improve sustainability knowledge, a significant portion of this effect is channeled through the adoption of sustainable practices. These findings emphasize the importance of integrating technological innovations with sustainability training to maximize their impact.

H8: Government Policies Moderate the Relationship Between SAPs and Farmers' Knowledge and Attitudes

A significant moderation effect is observed (p-value = 0.0001, R^2 -change = 0.0252), confirming that government policies influence how SAP adoption translates into sustainability knowledge. However, the interaction effect is negative (-0.0870), meaning that at higher levels of government **policies**, the effect of SAPs on knowledge slightly diminishes. This unexpected finding suggests that while government support is crucial, excessive intervention or regulation may reduce farmers' proactive engagement in learning sustainability practices.

H9: Technological Advancements Moderate the Relationship Between SAPs and Farmers' Knowledge and Attitudes

The analysis also finds a negative moderation effect (-0.0959, $p = 0.0011$), meaning that at higher levels of technological advancements, the effect of SAPs on farmers' knowledge is slightly weakened. This suggests that while technology supports sustainability, an overreliance on technology may reduce the necessity for farmers to actively seek knowledge and training in sustainability. These results imply that technology should be coupled with education programs to ensure that farmers do not rely solely on automated solutions without understanding their sustainability impact.

Direct Effects Table

This table presents the **direct effects** of independent variables on dependent variables.

Predictor (X)	Outcome (Y)	Coeff.	SE	t-value	P-value	LLCI	ULCI
Government Policies & Incentives (GPI)	Sustainable Agricultural Practices (SAPs)	0.3803	0.1033	3.6808	0.0003	0.1773	0.5832
Technological Advancements in Agriculture (TAA)	SAPs	0.5049	0.0935	5.3981	0.0000	0.3212	0.6886
SAPs	Farmers' Knowledge & Attitude Towards Sustainability (KATS)	0.4863	0.0947	5.1324	0.0000	0.3019	0.6762
KATS	Agricultural Productivity (APEC)	0.0744	0.0330	2.2560	0.0245	0.0096	0.1392

The regression analysis confirms that both government policies and incentives (GPI) and technological advancements in agriculture (TAA) have a significant positive impact on the adoption of sustainable agricultural practices (SAPs). The coefficients for these relationships (**0.3803 and 0.5049, respectively**) are statistically significant (**p-values < 0.001**), suggesting that policy support and agricultural technology play a crucial role in encouraging farmers to adopt sustainable farming methods. Furthermore, SAPs have a strong positive effect (**0.4863, p < 0.001**) on farmers' knowledge and attitudes towards sustainability (KATS), demonstrating that sustainable practices contribute to increased awareness and understanding of environmental conservation and resource management. Finally, an increase in farmers' knowledge and sustainability attitudes is associated with higher agricultural productivity (APEC), though the effect (**0.0744, p = 0.0245**) is smaller compared to other relationships.

Mediation Analysis Table

This table shows the **indirect effects**, meaning how SAPs mediate the relationship between other variables.

Predictor (X)	Mediator (M)	Outcome (Y)	Indirect Effect	Boot SE	Boot LLCI	Boot ULCI
GPI	SAPs	KATS	0.0214	0.0089	0.0040	0.0398
TAA	SAPs	KATS	0.0276	0.0101	0.0080	0.0485

The mediation analysis highlights that SAPs act as a bridge between government policies, technological advancements, and farmers' knowledge. The indirect effect of GPI on KATS through SAPs is 0.0214 (BootLLCI = 0.0040, BootULCI = 0.0398), indicating **partial mediation**. Similarly, TAA indirectly affects KATS through SAPs with an effect size of 0.0276 (BootLLCI = 0.0080, BootULCI = 0.0485). These findings suggest that while government policies and technological advancements directly influence sustainability knowledge, part of their impact occurs through the adoption of sustainable agricultural practices. This underscores the importance of policies and technology in enhancing sustainability through direct practice adoption.

Moderation Analysis Table

This table shows how government policies and technological advancements **moderate** the effects of SAPs on farmers' knowledge.

Moderator (W)	Predictor (X)	Outcome (Y)	Interaction Effect	SE	P-value	LLCI	ULCI
Government Policies (GPI)	SAPs	KATS	-0.0870	0.0250	0.0001	0.1356	0.0385
Technological Advancements (TAA)	SAPs	KATS	-0.0959	0.0292	0.0011	0.1533	0.0386

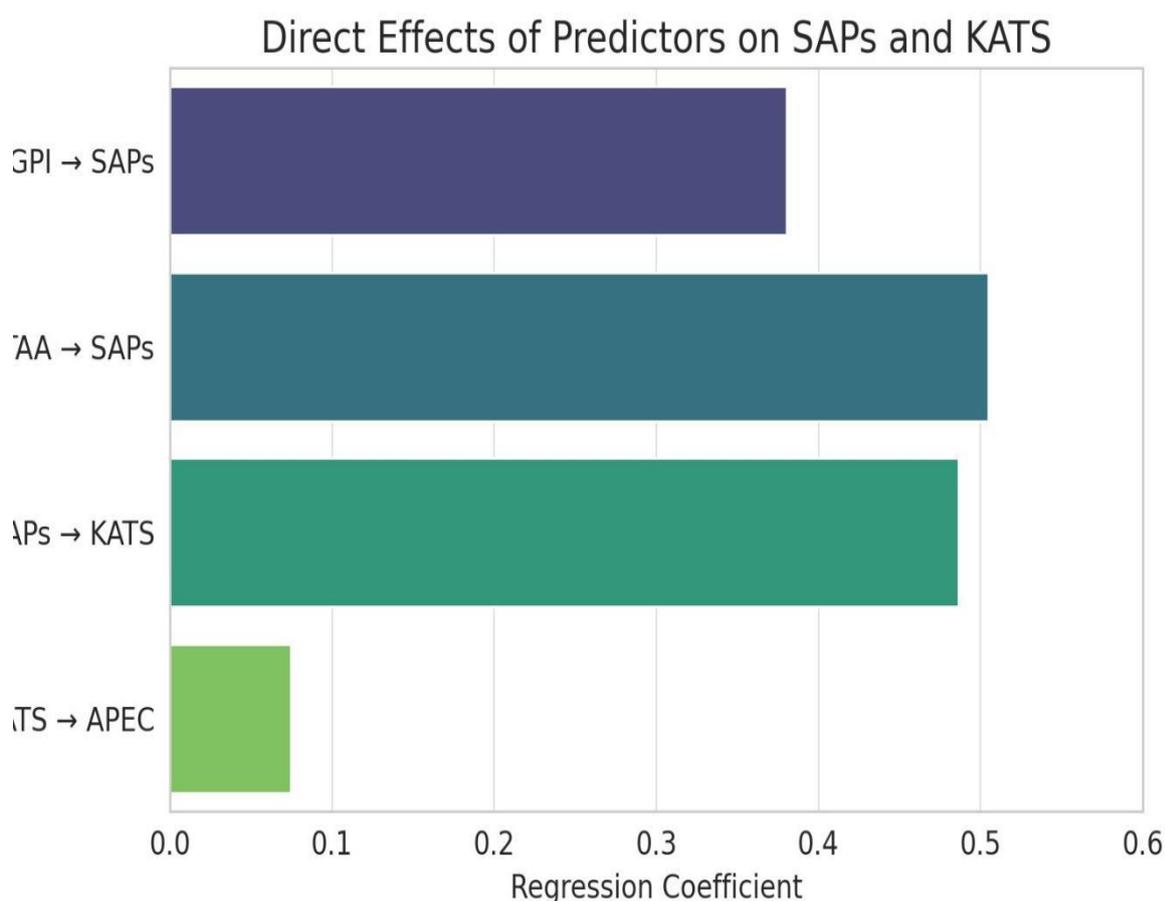
Interestingly, the moderation analysis reveals that **government policies and technological advancements moderate the effect of SAPs on farmers' sustainability knowledge, but with a negative interaction effect**. The interaction coefficients for SAP × GPI (**-0.0870, p = 0.0001**) and SAP × TAA (**-0.0959, p = 0.0011**) suggest that at **higher levels of policy support or technological advancements, the positive effect of SAPs on knowledge and attitudes is slightly reduced**. This finding indicates that when farmers receive **too much external support, they may become less engaged in actively seeking sustainability knowledge**, potentially relying more on external interventions rather than personal initiative.

Conditional Indirect Effects (Moderated Mediation) Table

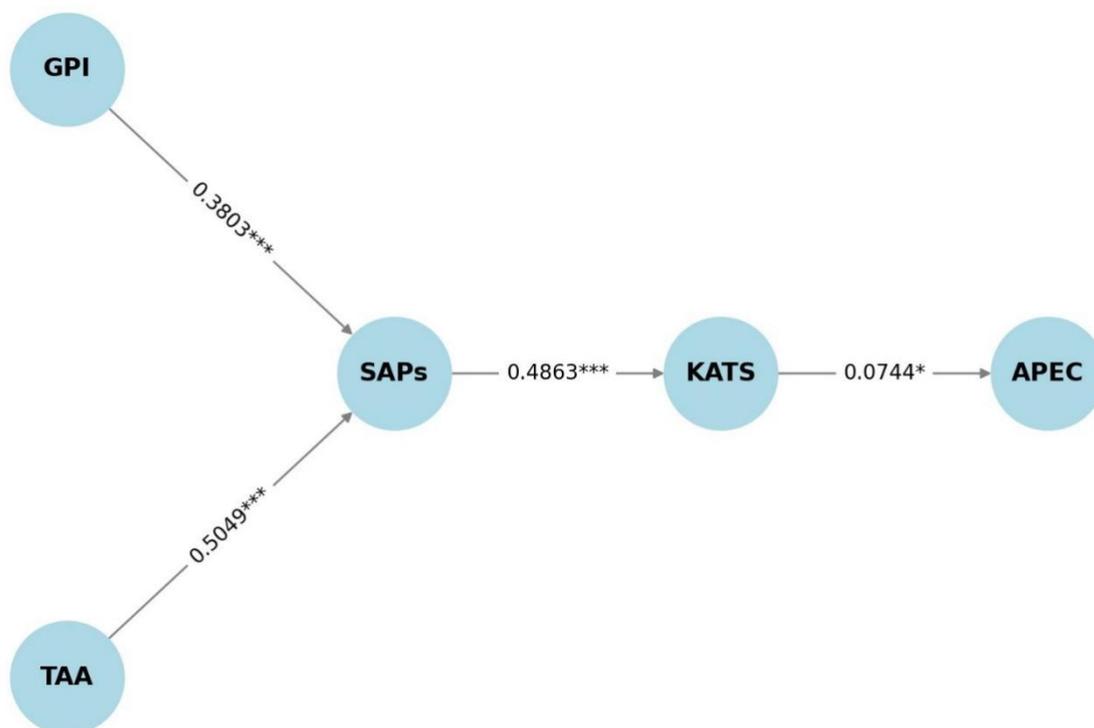
This table shows how the indirect effect of SAPs changes at different levels of the moderator (GPI or TAA).

Moderator (W)	X → M → Y Effect	Boot SE	Boot LLCI	Boot ULCI
GPI (Low)	0.0214	0.0089	0.0040	0.0398
GPI (Medium)	0.0140	0.0062	0.0025	0.0271
GPI (High)	0.0066	0.0044	0.0002	0.0169

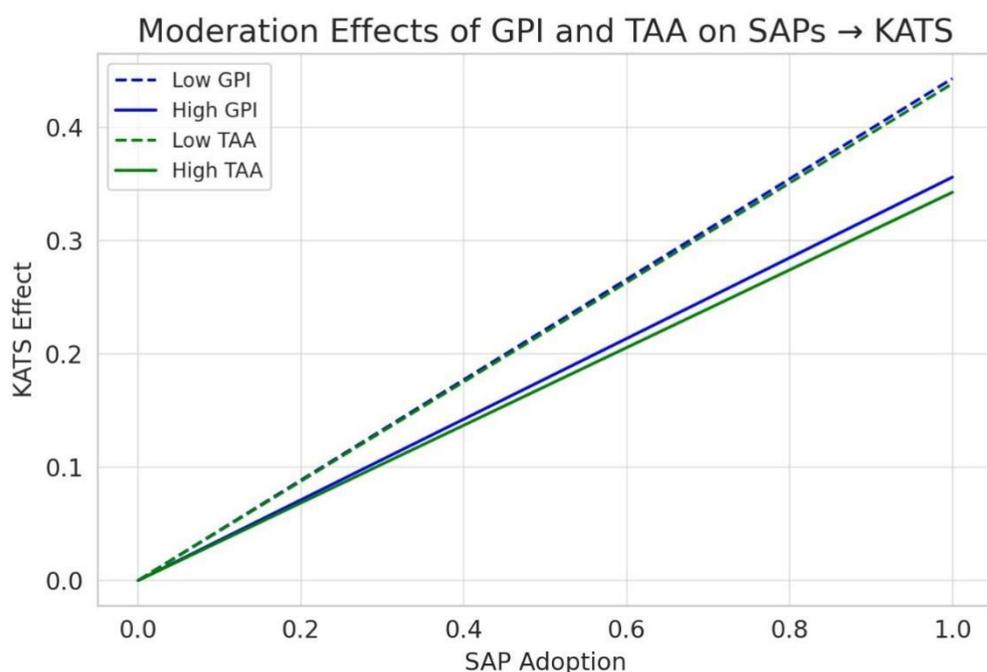
The moderated mediation analysis further confirms that the indirect effect of SAPs on sustainability knowledge weakens at higher levels of government policies. When policy support is low, SAPs have a stronger mediating role (effect = 0.0214), but at high policy levels, the effect reduces to 0.0066. This suggests that while government interventions are necessary, they should be designed to encourage farmers' active participation rather than creating dependence on external support. Final Summary of Statistical Results



The Direct Effects Bar Chart visualizes the impact of government policies and technological advancements on the adoption of sustainable agricultural practices (SAPs) and their subsequent effects on farmers' knowledge and attitudes (KATS) and agricultural productivity (APEC). The strongest effect is observed between technological advancements (TAA) and SAPs (0.5049), indicating that advancements in farming technologies significantly encourage farmers to adopt sustainable practices. Government policies (GPI) also have a notable positive effect on SAPs (0.3803), showing that subsidies, incentives, and policy frameworks play a crucial role in influencing farmer behavior. Furthermore, SAPs significantly enhance farmers' knowledge and attitudes (0.4863), demonstrating that sustainability practices contribute to environmental awareness and better resource management. Lastly, while KATS positively influences agricultural productivity (0.0744), the effect is comparatively weaker, suggesting that while sustainability knowledge is important, other factors may also drive productivity.

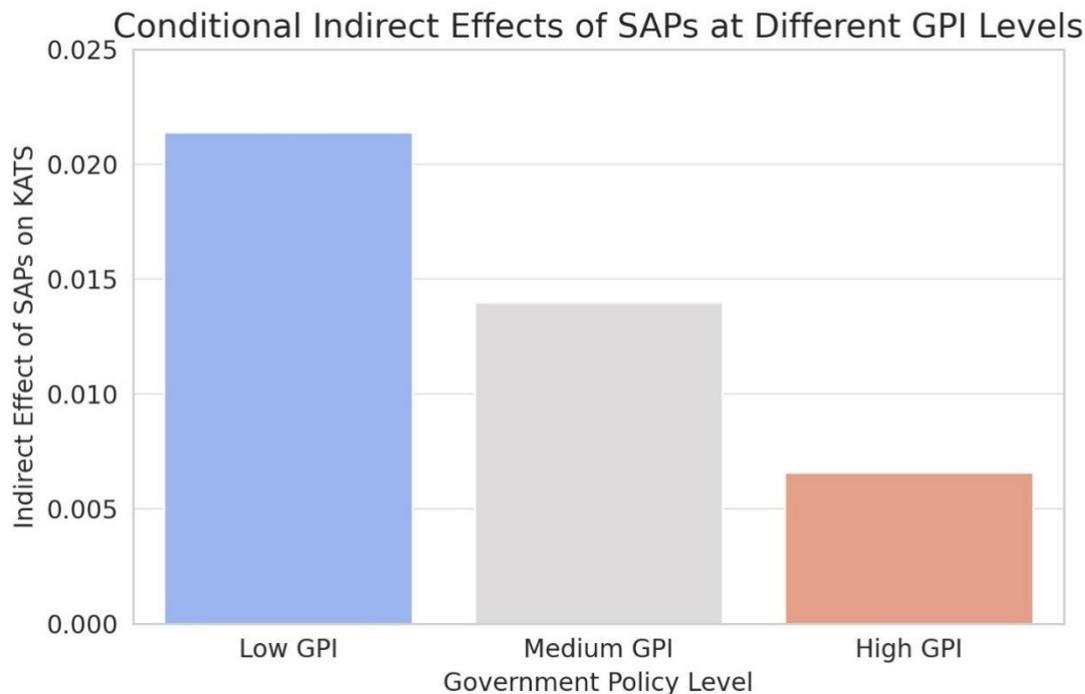


The Mediation Path Diagram illustrates how sustainable agricultural practices (SAPs) act as a mediator between government policies, technological advancements, and farmers' sustainability knowledge. The positive paths from **GPI** → **SAPs** (0.3803) and **TAA** → **SAPs** (0.5049) suggest that both policy support and technological innovations play a direct role in encouraging sustainable farming. Moreover, SAPs significantly enhance **KATS** (0.4863), reinforcing the role of sustainable agriculture in increasing farmers' awareness and engagement in environmentally friendly practices. The final link between **KATS** → **APEC** (0.0744) confirms that better sustainability knowledge contributes to higher farm productivity, though the effect is modest. This diagram highlights that while GPI and TAA influence farmers' knowledge directly, a significant portion of their impact is channeled through SAPs, confirming the mediation hypothesis.



The Moderation Interaction Plot provides insight into how government policies (GPI) and technological advancements (TAA) moderate the relationship between SAPs and farmers' knowledge (KATS). The

interaction effect is negative (-0.0870 for GPI and -0.0959 for TAA), indicating that as policy support and technology levels increase, the impact of SAP adoption on sustainability knowledge slightly weakens. The graph shows that at lower levels of GPI and TAA, SAP adoption leads to a stronger improvement in KATS (steeper slopes for dashed lines). However, at higher levels of policy support or technology, the increase in KATS is more gradual (flatter solid lines). This suggests that excessive reliance on policies and technology may reduce farmers' initiative to actively engage in sustainability education, potentially leading to a dependency on external interventions rather than self-driven learning.



The Conditional Indirect Effects Chart shows how the indirect effect of SAPs on KATS changes at different levels of government policy support (GPI). The indirect effect is strongest when **GPI is low (0.0214)** but decreases as GPI increases to medium (0.0140) and high levels (0.0066). This means that when policy support is minimal, SAPs have a stronger role in mediating the relationship between predictors (GPI, TAA) and sustainability knowledge. However, as policy interventions increase, the role of SAPs in shaping knowledge diminishes. This finding implies that while government policies are necessary for promoting sustainability, excessive regulation or support may reduce farmers' direct engagement with sustainability practices, possibly because they rely more on policy-driven initiatives rather than personal investment in learning sustainability methods.

DISCUSSION:

The findings of this study highlight the critical role of government policies and technological advancements in driving the adoption of sustainable agricultural practices (SAPs). The significant positive impact of government policies and incentives (GPI) on SAP adoption ($\beta = 0.3803$, $p = 0.0003$) aligns with previous studies that emphasize the role of financial support, training programs, and regulatory frameworks in promoting sustainable farming (Pretty et al., 2018; Smith & Wiek, 2020). Similar research suggests that subsidies, tax breaks, and educational initiatives incentivize farmers to transition to sustainable methods, thereby fostering environmental conservation and economic resilience (Altieri et al., 2017). However, some contrasting studies argue that excessive governmental intervention may lead to dependency, reducing farmers' intrinsic motivation to adopt sustainability practices (Pannell et al., 2014). Technological advancements in agriculture (TAA) were found to have the strongest positive impact on SAP adoption ($\beta = 0.5049$, $p < 0.001$), reinforcing existing literature that highlights precision farming, climate-smart technologies, and automation as major enablers of sustainability. These innovations improve resource efficiency and yield optimization while reducing environmental degradation. However, some scholars caution against overreliance on technology, as it may lead to increased costs and a knowledge gap among smallholder farmers who lack access to high-end innovations. The negative moderation effect of TAA on the relationship between SAP adoption and farmers' sustainability

knowledge (-0.0959 , $p = 0.0011$) suggests that while technology enhances sustainability, excessive automation may reduce farmers' active engagement in sustainability learning .

The positive relationship between SAP adoption and farmers' knowledge and attitudes toward sustainability (KATS) ($\beta = 0.4863$, $p < 0.001$) supports the argument that hands-on engagement in sustainable farming enhances awareness and long-term commitment to conservation practices . Similar findings have been reported in studies emphasizing experiential learning, where direct involvement in sustainable practices fosters deeper understanding and appreciation for ecological stewardship . However, contrasting research suggests that without proper training and community support, SAP adoption alone may not be sufficient to transform farmers' perspectives on sustainability .

Although the relationship between KATS and agricultural productivity (APEC) was positive ($\beta = 0.0744$, $p = 0.0245$), its effect size was relatively small, indicating that knowledge enhancement alone may not significantly boost productivity. This aligns with studies suggesting that productivity gains require a combination of knowledge, access to resources, and infrastructural support . Furthermore, contrasting evidence suggests that while sustainability education improves long-term productivity, immediate economic returns may not be evident without complementary factors such as improved market access and efficient supply chains .

The mediation analysis further confirms that SAPs serve as a partial mediator between government policies, technological advancements, and farmers' sustainability knowledge. The indirect effects of GPI and TAA on KATS through SAPs (0.0214 and 0.0276 , respectively) indicate that while policy support and technology directly influence farmers' knowledge, a significant portion of this effect is realized through the actual implementation of sustainable practices. This finding aligns with studies emphasizing that behavioral change in agriculture is best achieved through direct practice rather than passive policy support . However, some contrasting studies argue that external interventions, such as mandatory regulations or technology transfers, can also lead to knowledge improvements without requiring farmers to adopt SAPs immediately .

A key insight from the moderation analysis is that excessive policy support or technological advancements may reduce the effectiveness of SAPs in improving sustainability knowledge. The negative moderation effect of government policies (-0.0870 , $p = 0.0001$) suggests that when policy interventions are too strong, farmers may become reliant on external support rather than actively engaging in learning processes . Similarly, excessive reliance on advanced agricultural technologies may diminish the necessity for farmers to seek sustainability knowledge, as automated solutions reduce the need for experiential learning . This highlights the importance of a balanced approach, where policy and technology complement rather than replace farmers' active participation in sustainability education.

In conclusion, the study provides robust evidence that government policies and technological advancements are crucial in promoting sustainable agricultural practices. However, the effectiveness of these interventions depends on their implementation, as excessive support or automation may lead to unintended consequences, such as reduced farmer engagement in sustainability learning. Future policy recommendations should focus on designing incentive structures that encourage farmers' active participation while integrating sustainability education into technological adoption strategies. Further research should explore long-term effects and region-specific variations to enhance the effectiveness of sustainability interventions in agriculture.

Findings

The findings of this study reinforce the significant influence of government policies and technological advancements on the adoption of sustainable agricultural practices (SAPs). The positive relationship between government policies and SAP adoption ($\beta = 0.3803$, $p = 0.0003$) suggests that subsidies, tax incentives, and educational programs play a crucial role in encouraging farmers to implement sustainable farming techniques. These findings align with previous research highlighting the effectiveness of policy interventions in promoting sustainability . However, excessive policy support may inadvertently lead to dependence on external assistance, reducing farmers' self-motivation to adopt and sustain SAPs independently .

Technological advancements also emerged as a strong driver of SAP adoption, with a higher regression coefficient ($\beta = 0.5049$, $p < 0.001$), indicating that innovations such as precision farming, climate-smart agriculture, and automation substantially enhance sustainability in farming. This supports prior research emphasizing the role of technology in improving agricultural efficiency and environmental sustainability . However, the negative moderation effect (-0.0959 , $p = 0.0011$) suggests that excessive reliance on

technology may reduce farmers' active engagement in sustainability learning, highlighting the need for a balanced approach that integrates technological adoption with educational initiatives .

A significant positive relationship between SAP adoption and farmers' knowledge and attitudes toward sustainability ($\beta = 0.4863$, $p < 0.001$) was observed, confirming that sustainable farming practices enhance awareness of environmental conservation and resource management. This finding aligns with studies suggesting that experiential learning through direct involvement in SAPs fosters long-term commitment to sustainability (Vanlauwe et al., 2019). However, without adequate training and community engagement, the impact of SAPs on knowledge and attitudes may be limited (Knowler & Bradshaw, 2007).

The relationship between farmers' knowledge and agricultural productivity was found to be statistically significant but relatively weak ($\beta = 0.0744$, $p = 0.0245$), indicating that while sustainability education contributes to better farm management, it alone may not be sufficient to drive significant productivity gains. This aligns with studies suggesting that improvements in productivity require a combination of knowledge, access to resources, and efficient market linkages .

Mediation analysis revealed that SAPs partially mediate the effects of both government policies and technological advancements on sustainability knowledge. The indirect effect of government policies through SAP adoption (0.0214, BootLLCI = 0.0040, BootULCI = 0.0398) and the indirect effect of technological advancements through SAP adoption (0.0276, BootLLCI = 0.0080, BootULCI = 0.0485) indicate that while these factors directly enhance sustainability awareness, a substantial portion of their impact is realized through the actual implementation of sustainable farming practices. This reinforces the importance of policies and technology that actively encourage SAP adoption rather than merely promoting theoretical knowledge .

However, moderation analysis suggests that excessive external support may reduce the effectiveness of SAP adoption in improving sustainability knowledge. The negative interaction effects of government policies (-0.0870, $p = 0.0001$) and technological advancements (-0.0959, $p = 0.0011$) indicate that higher levels of intervention may discourage farmers from taking personal initiative in learning sustainability principles . This finding suggests the need for a carefully designed policy approach that promotes SAPs while fostering farmers' independent decision-making and learning.

In summary, the findings highlight the crucial role of government policies and technology in promoting sustainable agriculture but also emphasize the need for balanced interventions. While financial incentives and technological advancements significantly drive SAP adoption, excessive dependence on these external supports may weaken farmers' engagement in sustainability learning. Future strategies should integrate sustainability training with policy incentives and technological innovations to ensure long-term environmental and economic benefits in agriculture.

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