Google Scholar Crossref doi scopus

Impact factor 6.2

Geoscience Journal

ISSN:1000-8527

Indexing:

- Scopus
- Google Scholar
- DOI, Zenodo
- Open Access

www.geoscience.ac

Registered

AI-enabled green agriculture cooperation between China and Pakistan: optimizing grain production and Supply chain sustainability

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A B S T R A C T

The world faces some of the biggest problems, such as food insecurity, environmental degradation, and resource wastage, which can only be solved through sustainable agricultural practices. This has encouraged the green agriculture cooperation between China and Pakistan (ACCP), emphasising the integration of advanced technologies. In this regard, artificial Intelligence (AI) and green practices present a revolutionary approach to advancing sustainability in agriculture. This study proposes to assess the influence of AI capability (AIC), farmer green values (FGV), green innovative intentions (GIN), and energy-use reduction (ERD) towards the "adoption of green production" (AGP). Further, it evaluates the mediation of the sustainability of the supply chain (SCC) on these relationships and the moderation of eco-innovation (ENI) in the association between SCC and green production adoption. A quantitative research approach was applied, and the data was gathered via a survey questionnaire that was administered online through Qualtrics. The sample consisted of 294 farmers/ employees, working under ACCP projects and SEM was used for analysis. The study results showed that FGV, GIN and ERD have a significant impact on AGP ($p < 0.05$) while AIC was found to have an insignificant association with AGP ($p > 0.05$). Supply chain sustainability mediates these effects ($p < 0.05$), and eco-innovation enhances the influence of sustainability on green production ($p < 0.05$). The study makes practical contributions by highlighting the need to integrate AI, sustainability practices, and eco-innovation in agriculture. Thus, policymakers and agricultural firms can use these findings effectively to develop agendas promoting increased green production and international cooperation. The information presented provides a model for other areas interested in enhancing food yield while minimising adverse environmental impact through technology and new advancements.

Keywords: *AI capability, agriculture, green values, supply chain sustainability, China, Pakistan.*

1. Introduction

Agriculture is a central part of Pakistan's economy, as it accounts for approximately 18.9% of the Gross Domestic Product (GDP) of the nation and employs roughly 42.3% of the nation's workforce (Agriculture-Policy-Institute-Pakistan, 2023). Pakistan's GDP in agriculture was recorded at 8.9 PKR Million in 2023 compared to 8.7 PKR Million in 2022. The average GDP from agriculture in Pakistan is 6.7 PKR Million from 2000 to 2023, and the maximum value is recorded at 8.98 PKR Million in 2023 (figure 1). This makes it, one of the main producers of agricultural products worldwide. As a result, Pakistan has become one of the main exporters of agricultural products to China. In recent years, Pakistan's exports of high-quality agricultural products including mango, nuts, rice and sesame, have increased. This led to the agricultural cooperation between China and Pakistan, under the “China-Pakistan Economic Corridor (CPEC)” (CPEC, 2024a). It is a progressive measure that guarantees grain productivity and streamlines supply chains (Butt, 2023).

Figure 1. Pakistan's GDP from agriculture

(Source: State-Bank-of-Pakistan (2024)

Different agreements have been signed between China and Pakistan to introduce "AI-based agricultural machinery" in Punjab to make significant agricultural advancements (CPEC, 2024b). Therefore, the application of Artificial Intelligence (AI) and smart farming seeks to solve some significant issues affecting the farmers in Pakistan, which include the effects of climate change, poor farming techniques, and food insecurity (Naz et al., 2024). Today, many AI technologies, like drones with video analysis capabilities, make it possible to automate several procedures, including crop inspection, pest survey, and irrigation control for farmers. This not only increases productivity but, more importantly, lowers operational expenses considerably (Sharma & Shivandu, 2024). The decided partnership between Pakistan and China also has a strategy to send 1000 directorates of agriculture to China for their orientation to modern methodologies and information exchange. It will help implant the requisite AI technology in Pakistan's agricultural field. In adopting these innovations, Pakistan plans to enhance crop productivity to reframe the agrarian practices for sustainability given environmental adversities (SAMAA-Web-Desk, 2024).

The global pressure to feed the world's growing population while preserving production and the environment necessitates pursuing modern approaches such as AI-driven green agriculture (Christo & Mailera, 2024). In the context of China and Pakistan, where agriculture serves as a chief mode of economic growth, it is pertinent to implement eco-friendly production strategies to tackle problems relating to resource availability, the deterioration of the climate, and many others concerning the supply chain (Dogar, 2023). Nevertheless, applying AI technologies to promote green production is still challenging because of the lack of necessary infrastructure, low levels of awareness among farmers, and an irregular supply chain (Köster et al., 2024). Past research has mainly focused on AI integration in the agriculture sector of different agricultural countries such as China, India and others (Chatterjee et al., 2023; Zhou et al., 2024), however, limited focus has been given to the role of AI in increasing green production and sustainable supply chain within the context of Pakistan and China cooperation. Thus, this study has been effective in filling this knowledge gap. In this regard, the role of green innovation intention (GIN) is also inevitable. The developed nations are considered to have an effective association between GIN and AI adoption than developing nations due to technology complexities and different economic landscapes (Wang et al., 2025). This study also contributes to the literature regarding this association, within the context of "agricultural cooperation between Pakistan and China" (ACCP). Due to persistently increasing competition in the agriculture sector, the significance of sustainable agriculture has been elaborated, emphasising the implementation of AI technologies (Hamed et al., 2024). However, this association is discretely addressed within the context of green culture cooperation between Pakistan and China (two of the major agricultural countries in the world). However, limited focus has been given to the role of eco-innovation (ECI) in influencing the adoption of green production (AGP) within the coagulating agricultural systems in China and Pakistan (Buchana, 2023; Elahi et al., 2022). Past studies have recognised the roles of AI and green values in shaping sustainable agriculture (Ashraf & Akanbi, 2023; Nancy & Kiran, 2024), whereas, limited focus has been given to eco-innovation and energy consumption reduction within the context of AGP. However, Buchana (2025) has emphasised the integration of ECI to promote agricultural sustainability. For this purpose, agricultural businesses need to invest in process innovations and technologies. This strategy is also acknowledged for the China and Pakistan agricultural cooperation. In this regard, the current research has also focused on the moderating role of ECI in the relationship between sustainable supply chain (SCC) and AGP. Moreover, the moderation of eco-innovation in the context of SCC and green production adoption has not been studied extensively (Buchana, 2023), encouraging the current research to overcome this gap. According to Elufioye et al. (2024), AI technology is also effective in improving efficiency and accuracy within agricultural supply chains as it incorporates real-time data analysis. However, different challenges can also be faced in implementing AI technology in agricultural supply chains which include infrastructural development, skill gaps among farmers and data quality. Another theoretical discrepancy includes the mediating role of SCC in the association between AI capability, green values, innovation intentions, energy efficiency, and green production adoption (Martínez-Falcó et al., 2023; Nayal et al., 2023).

In order to bridge the identified research gaps, this research aims to assess the impact of green production drivers including AI capability (AIC), farmer green values (FGV), green innovation intention (GIN), and energy use reduction (ERD), on the adoption of green production technology (AGP). In addition, the mediation of a sustainable supply chain (SCC) and the moderation of eco-innovation (ECI) is also determined.

Therefore, in this study, the main focus is given to the agricultural cooperation potential between Pakistan and China, emphasising the significance of ECI and AGP. This has added novelty to current research. This study is also vital in evaluating the role of China, in contributing to the development of green agriculture in Pakistan. This approach can also be beneficial for increasing food security in China, as it largely imports agriculture and other food products from Pakistan (Khan, 2024). In addition, the evaluation of AGP and AIC in influencing SCC between China and Pakistan has also enhanced the innovativeness of this research, making it an essential part of academic research within the context of green agriculture technology.

According to Gao and Zhang (2022), farmers are often hesitant about the acceptance of innovative green technology. This resistant behaviour is common among farmers in conventional countries like Pakistan (Elahi et al., 2022). Thus, this study will be effective in promoting green technology and ECI in Pakistan's agriculture sector to encourage the farmers to improve the production and supply chain of different crops. This can result in increased GDP growth of the nation. At the same time, this study can also provide important policy recommendations for developing a robust regulatory framework to promote AGP and other joint green agricultural ventures between Pakistan and China.

2. Literature review

2.1. Theoretical framework

The Technological-Organisational-Environmental (TOE) framework, mainly focuses on the adoption and implementation of technological innovations by the organisation. It determines the role of three important factors (including environment, organisation and technology) in influencing technology adoption (Nagy et al., 2025). Therefore, this framework is suitable for understanding the adoption of AI-driven green agriculture within the context of "agricultural cooperation between China and Pakistan

(ACCP)." From the technological perspective, the framework identifies AI solutions' applicability, sophistication and relevance to the agriculture value chain. This entails assessing relatively compound technologies like precision farming, analytical tools and sophisticated irrigation to reinforce grain production without compromising effectiveness and sustainability (Elufioye et al., 2024). Organisational factors support the readiness and capacity of agricultural actors – policy makers, supply chain actors, and farmers to adopt technological innovations in their practices (Penone et al., 2024). It is, therefore, stated that success in terms of strategic goals requires technical competency and a culture that embraces change. Specifically, partnerships between the public and private sectors and knowledge transfer are essential for growth and sustainability (van Ewijk & Ros-Tonen, 2021).

From the environmental perspective, this framework focuses on regulation policies and constraints, such as ecological limitations and opportunities, as well as the market forces shaping sustainability practices (Lutfi et al., 2023). Inadequate access to physical capital, weak infrastructure development, and vulnerability to climatic changes can, however, be subdued with the help of supportive government policies and cross-border cooperation between China and Pakistan (Butt, 2023). Moreover, international cooperation and funding help industries change supply chains for sustainability goals and increase food availability. The TOE framework can thus be used to provide a strong understanding of the various procedures included in the application of AI in the advocacy of economical and environmentally viable trade in farming (Ndlovu et al., 2023).

Therefore, the TOE framework can be applied to this research since it enables an understanding of how the ACCP can contribute to the deployment of AI solutions because it incorporates various aspects of the process of deploying new technologies. A past study by Nagy et al. (2025), also determined the association between agricultural SMEs' performance and TOE construction. It has been observed that the synergy between Industry 4.0 and technology adoption in agricultural firms, can enhance automation and connectivity. These are important factors in promoting smart agriculture. However, different challenges which can be faced in this regard, include effective management of organisation, resources and external/ internal organisational environments. Therefore, the TOE framework has been used to determine the association between AIC, FGV, GIN, ERD and AGP.

2.2. AI capability and adoption of green production

Recently AI is being applied within farming to cultivate healthy crops and to monitor soil. This technology is also found to be effective for managing pests and managing food supply chain activities. Therefore, AI-powered solutions are considered to be effective for farmers in producing more crops by using limited resources (Javaid et al., 2023). This supports the integration of AI technology to improve AGP. Other cutting-edge technologies such as AI, big data analytics, blockchain and quantum computing are also considered to have a significant impact on the production system's sustainability (Chatterjee et al., 2023). However, technology turbulence can negatively influence technology adoption. This can negatively impact the sustainability of relevant adoption systems.

Therefore, modern, sophisticated, intelligent technologies, including machine learning, predictive analytics, and automation, enhance the efficient use of resources, control wastage, and decrease adverse effects on the environment (Alsabt et al., 2024). For example, AI solutions can forecast meteorological conditions, analyse the quality of soil, and control watering, which leads to high accuracy in agricultural work. Moreover, AI supports decision-making since it provides timely information and solutions, which allows stakeholders to adopt environmentally friendly processes (Akintuyi, 2024). Therefore, through optimality in operations and contribution to the improvement of sustainability, AI capability covers both the economic and ecological aspects, which are key in the implementation of green production across various industries (Hernandez et al., 2024). This can support the AGP to achieve a competitive advantage. Therefore, it can be hypothesised that:

H1: AIC positively impacts the AGP.

2.3. Farmer green values and adoption of green production

FGV play a significant role in adopting the practices related to green production due to their role in promoting environmental awareness among farmers. Farmers will likely implement environmentally friendly practices where sustainability is valued, including organic farming, precision cropping, and resource conservation. These values improve practices like water conservation, reduction of the use of chemicals, and preserving biological diversity (Zavhorodnii et al., 2024). According to Paltasingh and Goyari (2018), schooling is very essential for farmers as it helps in enhancing farmer's skills and capabilities regarding green production. Furthermore, farmers with high green values perceive efficient sustainability as a means of improving the farming systems and making farming more secure in the future (Perrin et al., 2020). Therefore, such commitment fosters innovation, partnership, and adoption of sustainable solutions that lead to the enhancement of sustainable practices in the agricultural domain (Khan et al., 2021; Matos et al., 2022).

In earlier studies, researchers have noted that farmers' environmentalism drives the practice of sustainable agriculture as its foundation is based on resource conservation, maintaining biological diversity, and long-term income from production. However, these works do not systematically examine how such values can be connected to technological progress, international relations, or certain regions. The present study addresses this shortcoming by investigating the farmers' green value orientations and the role of AI within the context of ACCP. Thus, it can be hypothesised that:

H2: FGV positively impacts the AGP.

2.4. Green innovative intentions and adoption of green production

GINs are significant in AGP because they encourage firms to pursue proactive sustainability and innovation. Past research has also emphasised the role of GIN in influencing AGP. For instance, a past study by Gao et al. (2022), presented a significant association between GIN and adoption of green technology. GIN is also found to have a significant mediation in the relationship between FGV and the adoption of green technology. This emphasises the significance of GIN in impacting AGP within the context of ACCP. Another study by Bhatti and Juhari (2023), showed that sustainable behaviours and attitudes significantly impact green innovation adoption. In contrast, social perception does not have a significant impact on green innovation perception. In this regard, the utilisation of advanced technology such as blockchain technology is also considered to be vital for influencing GIN.

Therefore, it is essential to adopt green technologies and processes to develop environmental solutions and policies (Shahzad et al., 2022). By adopting this core value, stakeholders can identify innovative solutions towards tackling environmental issues, increasing resource utilisation efficiencies, and minimising ecological impacts. Such a commitment to green innovation promotes sustainability, creates awareness and changes in providing sustainable production systems, and sustains long-term environmental and economic objectives (Shan & Ji, 2024). Therefore, it can be hypothesised that:

H3: GIN positively impacts the AGP.

2.5. Energy use reduction and adoption of green production

Energy consumption is found to be increasing in the agriculture sector in different European Union (EU) nations. This largely contributes to climate change and global warming. As a result, important measures are being taken by different agriculture companies to utilise renewable energy sources to promote sustainability in the agricultural sector (Rokicki et al., 2021). As a result, the agricultural sector has seen various transformations within the context of energy consumption, across the globe (Peng et al., 2024). The reduction in energy usage also benefits the adoption of green production through the synergy of environmental gains and economic savings. It is also beneficial in cutting expenses; hence, it is more feasible for producers to embrace sustainable development (Kristian et al., 2024). It also helps reduce emissions of greenhouse gases, so it plays its role in the protection of the environment and adherence to regulatory measures. These reductions are possible through improved technologies like renewable energy sources and energy-efficient production equipment that do not compromise production efficiency (Majeed et al., 2023). Further, lower energy consumption is associated with less environmental impact, thus improving the company's image and competitiveness. ERD should, therefore, be embraced throughout the industries that engage in green production since it acts as a lever to promote other green production practices (Afum et al., 2020).

Prior research focuses on the benefits of green production and emphasises the association between energy use reduction and costs, emissions, and compliance (Afum et al., 2020; Majeed et al., 2023). Nevertheless, these works do not encompass the analysis of the coordination between energy-saving measures and AI technologies in specific regional or cross-border settings. Furthermore, the part played by collaborative platforms in disseminating energy-efficient green practices is also a research gap that has not been well addressed. In this regard, the current study overcomes these gaps by determining the association between energy use reduction and AI-enabled green agriculture in China-Pakistan to understand better the roles and impacts of technological sustainability projects in an international context. Thus, it can be hypothesised that:

H4: ERD positively impacts the AGP.

2.6. Mediation of SCC

In the agricultural sector, the maintenance of an effective SCC is considered to be vital to ensure effective agricultural production. For this purpose, the integration of innovation solutions is considered to be pivotal within agricultural supply chains. Although different innovative solutions are available for improving SCC in the agriculture sector, still different challenges are observed in this regard (Mahroof et al., 2021). As a result, the issue of sustainable agri-food supply chain has gained interest due to increased awareness among people (Ricciolini et al., 2024). Big data and innovative technology such as AI, are considered to be effective in increasing supply chain transparency. These technologies are also found to be effective in improving resource utilisation and minimising costs. These improvements contribute to sustainability and offer a platform for green manufacturing practices (Arowosegbe et al., 2024). AI can, therefore, be adopted in supply chain processes to enhance environmental conservation and organisational operating strategies (Helo & Hao, 2022). This has accentuated AI-driven supply chain innovations to buttress sustainable output advancement across industries as it underlines how innovative supply chain measures of AI integrate with sustainability goals away from contradicting sustainable development (Sah et al., 2024).

Moreover, farmers with a high inclination towards green values, also focus on incorporating environmentally sustainable techniques to promote SSC. However, their success hinges on a sustainable procurement system, materials consumption efficiency, waste minimisation, and environmentally accredited supply chains (Asiedu-Ayeh et al., 2022). A SCC increases the impact of these values by pushing green practices beyond the production level. This underscores the relevance of matching farmers' environmental concerns towards broader systemic production change processes to foster green production uptake (Piñeiro et al., 2020). Similarly, energy consumption is also an essential factor within the context of SCC.

Lower energy utilisation means less expenditure and pollution, while its broader effectiveness is seen when integrated into a green purchasing system (Iqbal et al., 2020). The implementation of logistics management, efficient resource management, and proper management of waste promotes energy conservation with the promotion of eco-friendly production at all levels (Kumar & Muthulakshmi, 2023). This establishes how improved energy efficiency contributes to the greening of the supply chain at every stage while encouraging environmentally sustainable production (Gawusu et al., 2022).

Moreover, energy conservation has both cost-saving and environmentally friendly benefits; it also improves resource management and organisational productivity (Kristian et al., 2024). A sustainable supply chain multiplies these advantages by incorporating eco-friendly transport, warehousing, and delivery solutions. This guarantees that energy conservation measures lead to holistic green manufacturing systems, corporate sustainability, and supply chain robustness (Ahuchogu et al., 2024). The proposed hypotheses are:

H5: SCC mediates the relationship between AIC and the AGP.

H6: SCC mediates the relationship between FGV and the AGP.

H7: SCC mediates the relationship between GIN and the AGP.

H8: SCC mediates the relationship between ERD and the AGP.

2.7. Moderation of eco-innovation

In today's innovative agricultural sector, the integration of eco-innovation has become crucial. As a result, different agricultural businesses are taking important measures to invest in acquiring knowledge, utilising different technologies and developing process innovations (Buchana, 2025). These approaches are crucial to attain sustainable outcomes. Another past study by Wang et al. (2022), has emphasised the role of eco-innovation in improving the value chain within the agricultural sector. In this regard, the integration of green innovation is also considered to be vital. Moreover, in recent years, environmental awareness has increased among the users, which has encouraged the governments and associated agricultural companies to integrate eco-innovation. This has become an important competitive factor within the context of agricultural supply chains. Different factors such as cooperation strategies, social performance, business size and environmental regulation also influence the integration of eco-innovation in agricultural supply chains (Galera-Quiles et al., 2021).

Integrated high-tech solutions and innovative ideas further enhance the concept of sustainable supply chains by increasing effectiveness and involving environment-friendly processes. This makes sure that sustainable supply chain initiatives are more effective and applicable in promoting green manufacturing (Kalnyi, 2023). Therefore, through innovation, organisations can unlock factors that prevent the effective implementation of best supply chain practices that promote green change, hence enhancing both environmental and economic performance (Rehman Khan et al., 2022). Although past literature has focused on the association between SCI and SCCA within the context of the agricultural sector, no focus has been given to the moderation of ECI in the relationship between SCC and AGP. Therefore, this study has been effective in filling this gap. Thus, the following hypothesis can be proposed:

H9: ECI moderates the association between SCC and the AGP.

3. Research Method

3.1. Research Approach

The research study is quantitative due to numerical information and statistical tools to examine relationships between variables. This approach is suitable for testing hypotheses and the strength of relationships and offers accurate, consistent and generalisable results. Quantitative research allows the application of standard instruments like questionnaires or surveys, making data collection systematic. The added advantage of this approach is that it enables the rigorous use of theories by applying statistical techniques in the evaluation process and decision-making. The attributable structure makes it suitable for research studies intending to investigate causal relationships between critical variables (Mohajan, 2020).

3.2. Population and sample size

The population of this research consists of farmers/ employees, working in different agricultural projects under ACCP. This cooperation is formed under the China-Pakistan Economic Corridor (CPEC), making it an essential cooperation for agricultural sector development in Pakistan. Table 1 shows that the study has 39 items. According to the Item Response Theory, more than 390 questionnaires must be distributed (Schreiber, 2021). Hence, 450 questionnaires were administered among employees of agricultural firms in Pakistan and the CPEC Chinese Professionals. Of these, 400 were returned; thus, the initial response rate was considered high. However, based on the screening of the responses, the researcher was left with only 294 respondents in the study who filled out the questionnaire without any missing values. This final sample size was used for the analysis to ensure reliable and accurate results. This sample size made it easier to evaluate the research objectives using statistical procedures.

3.3. Data collection and sampling technique

Data was gathered through a structured questionnaire adapted from past studies, which was administered through Qualtrics; this made it easier for participants to access the questionnaire and respond promptly (Mahapatra, 2021). Convenience sampling was used to sample the respondents as it is easy and cheap to use when the sample population is easily accessible (Rashid et al., 2021). This approach is best suited for reaching out to participants with adequate understanding and experience while maintaining flexibility. It enables the sample size to be obtained within a short period, especially useful for research that focuses on specific details (Akkaş & Meydan, 2024).

3.4. Measures and scales

All the constructs were measured on a “5-point Likert Scale,” where “1: Strongly Disagree to 5: Strongly Agree.” The following table represents the constructs, their items no., and the sources of the scales:

Table 1

Construct, number of items, and scale sources

Construct	Number of items	Source of scale
AIC	4	Zhang et al. (2020), (adapted: Salehi and Burgueño (2018)), Goyache et al. (2001), and Kibria et al. (2018)
FGV	5	Al-Ghazali and Afsar (2021), (adapted: Chou (2014))
GIN	3	Al-Ghazali and Afsar (2021), (adapted: Norton et al. (2017))
ERD	7	Li et al. (2023), (adapted: Blasch et al. (2017))
AGP	11	Yu et al. (2022)
SCC	5	Bag et al. (2022), (adapted: Liu et al. (2018))
ECI	4	Marco-Lajara et al. (2023), (adapted: Hojnik et al. (2018))

3.5. Data Analysis

The quantitative data was analysed through "structural equation modelling," (SEM) ideal for research that seeks to establish the interconnectivity between various factors. This approach was chosen because it allows for the approximation of direct, indirect, and mediating effects and offers more profound insight into the relations in the context of the given research model. This technique involves using measurement models and structural models that help validate the newly developed constructs, as well as the testing of the research hypothesis (Al Masud et al., 2024). Its strengths are in its ability to accommodate latent variables and address the measurement error problem, enhancing the outcomes' quality (Hair Jr et al., 2020).

4. Results

4.1. Descriptive Statistics

Table 2 shows the results for "descriptive statistics (DS) and a correlation matrix (CM)" for the variables in the study. Results depict that the mean values range from 3.47 (ECI) to 4.18 (FGV). It shows generally favourable responses toward green and sustainable practices. The standard deviations are from 0.94 to 1.12, which shows a moderate variability in the responses across the sample of 294 participants. The correlation matrix also indicates significant relationships between several variables. In this regard, AGP has strong positive correlations with ERD (r= 0.602, $\mathbf{p < 0.01}$), FGV (r= 0.559, $\mathbf{p < 0.01}$), and SCC (r= 0.466, $\mathbf{p < 0.01}$). It highlights that these factors significantly contribute to the adoption of green production. Similarly, ERD has a significant association with FGV (r = 0.458, $\mathbf{p < 0.01}$) and SCC (r= 0.423, $\mathbf{p < 0.01}$). This underscores their interconnectedness regarding the promotion of energy efficiency. However, AIC is moderately correlated with AGP (r= 0.372, **$p < 0.01$**) and FGV (r= 0.389, **$p < 0.01$**). It shows its potential role in influencing sustainable practices.

Table 2 indicates that ECI has a weak but negative correlation with AGP (r= -0.121, $p < 0.05$), ERD (r= -0.134, $p < 0.05$), and FGV (r= -0.126, $p < 0.05$). It highlights a complex relationship that may require further investigation. GIN has a significant association with AGP (r= 0.233, **$p < 0.01$**) and SCC (r= 0.235, **$p < 0.01$**). It showed its potential to enhance green production through innovative intentions.

Table 2

DS and correlation and CM

	DS			CM						
Constructs	N	Mean	Std. Deviation	1	2	3	4	5	6	7
1.AGP	294	4.1296	.96391	1						
2.ERD	294	4.0549	.93925	.602**	1					
3.SCC	294	3.8116	1.12447	.466**	.423**	1				
4.FGV	294	4.1850	1.02357	.559**	.458**	.366**	1			
5.AIC	294	4.0264	1.01962	.372**	.336**	.316**	.389**	1		
6.ECI	294	3.4736	1.05519	-.121*	-.134*	.020	-.126*	-.122*	1	
7.GIN	294	3.5204	1.00782	.233**	.177**	.235**	.145*	.105	.237**	1

The model fit indices (MFI) indicate the data's good fit in association with the proposed model. The CMIN/df value resulted as 1.629 and was considered acceptable in this research in accordance with the research by Saleem et al. (2023). The "Comparative Fit Index" (CFI = 0.946) and "Tucker-Lewis Index" (TLI = 0.941) both exceed the recommended threshold (0.90) which underscored a strong model fit. In addition, the "Standardized Root Mean Square Residual" (SRMR = 0.061) and "Root Mean Square

Error of Approximation" (RMSEA = 0.046) are both below the recommended cutoff of 0.08 as explained in the research by Celestin et al. (2022) thus supports the fitness of the model. Details can be seen in Table 3:

Table 3

MFI assessment

FI	Recommended Val	Obtained Val
CMIN/df	1-3	1.629
TLI	> 0.90	.941
GFI	> 0.90	.841
SRMR	< 0.08	.061
CFI	> 0.90	.946
RMSEA	< 0.06	.046

Val= value

The following figure shows the measurement model:

Figure 2. Measurement model (CFA)

Table 4 presents the results of factor loadings (FL), normality, reliability, and validity tests for the study variables. Results indicated that the FL for all items exceeded the acceptable threshold of 0.60. It depicts that the items strongly represent their respective constructs. The values of Cronbach Alpha (CA) for all constructs have been reached above 0.70 (Tavakol & Dennick, 2011) which shows good internal consistency. Composite Reliability (CR) values for all constructs are greater than 0.70 (Sujati & Akhyar, 2020) which further confirms reliability. However, "Average Variance Extracted" (AVE) values are all above 0.50 (Yusoff et al., 2020). It depicted adequate convergent validity.

Skewness and kurtosis values also resulted in falling within acceptable ranges. It supports the assumption of normality for the data. The values of "Maximum Shared Variance" (MSV) are less than the values of AVE for all constructs of the study. It confirms the discriminant validity and explains that the constructs are distinct from one another. Thus, the results collectively determine the validity, suitability as well as reliability of measurement model for further analysis. It also ensures a vigorous foundation for assessing the associations among constructs.

(Table 4)

Table 5 presents the findings of the discriminant validity test. It confirms the distinctiveness of the constructs. The diagonal values show AVE's square root. In this regard, all the values exceed the inter-construct correlations in their respective rows and columns. This also satisfies the criterion by "Fornell-Larcker" and depicts good discriminant validity (Rasoolimanesh, 2022). The AGP indicates strong positive correlations with Energy Use Reduction (ERD; r=0.637, $p < 0.001$) and Farmer Green Values (FGV; r= 0.624, $p < 0.001$). It highlights their importance in attaining green production practices. Supply Chain Sustainability (SCC) also have a significant association with AGP (r= 0.505, $p < 0.001$) and ERD (r= 0.451, $p < 0.001$). AI Capability (AIC). It showed significant moderation with AGP (r= 0.411, $p < 0.001$) and FGV (r= 0.438, $p < 0.001$). The results underscore its significant role in supporting sustainable practices.

Conversely, Eco-innovation (ECI) resulted in have weak negative association with AGP (r= -0.128, †p < 0.10) and ERD (r= -0.141, *p < 0.05). Green Innovative Intentions (GIN) positively correlate with AGP (r= 0.258, $p < 0.001$) and SCC (r= 0.281, $p < 0.001$). It showed the potential through which green production can be enhanced through innovation. In this way, the results validate the distinctiveness of the constructs along with highlighting key associations between variables which are critical to sustainability and innovation.

Table 5

Discriminant validity test results

	AGP	ERD	SCC	FGV	AIC	ECI	GIN
AGP	0.775						
ERD	0.637***	0.820					
SCC	0.505***	0.451***	0.848				
FGV	0.624***	0.508***	0.412***	0.779			
AIC	0.411***	0.363***	0.347***	0.438***	0.808		
ECI	-0.128†	-0.141*	0.025	-0.138*	-0.136*	0.764	
GIN	0.258***	0.193**	0.281***	0.178**	0.128†	0.278***	0.825

Table 6 presents the direct effects results, thereby investigating the relationships between the independent variables (Energy Use Reduction [ERD], Farmer Green Values [FGV], AI Capability [AIC], and Green Innovative Intentions [GIN]) and the dependent variable, Adoption of Green Production (AGP). The results showed that ERD has a significant positive effect on AGP (β = 0.368, ***p* < *0.001***) which supports **H1**. This also indicates that efforts for the reduction of energy use strongly contribute to the adoption of sustainable practices of production. Similarly, FGV significantly influences AGP (β = 0.276, ***p* < *0.001***) which supports **H2**. This depicts that the values of farmers that focus on environmental sustainability play an important role in the adoption of green production. Results also indicated that AI Capability (AIC) does not significantly influence AGP (β = 0.073, *p* > *0.05*) which depicts the rejection of **H3**. This underscores that AI capability is important in theory. However, it might not directly drive green production practices mainly due to limitations in implementation or adoption. On the other hand, GIN positively impacts AGP (β = 0.076, *p* = *0.05*) which supports **H4**. This shows that intentions toward green innovation are a weaker predictor as compared to ERD and FGV. However, it still plays an important role in promoting sustainable production methods.

Table 6

Direct effects results

Relationship			Hypothesis	β	S.E.	C.R.	Beta	P-Value	Decision
AGP	<---	ERD	H1	.368***	.051	7.266	.358	.001	Accepted
AGP	<---	FGV	H2	.276***	.046	5.983	.293	.001	Accepted
AGP	<---	AIC	H3	.073	.044	1.683	.078	.123	Not accepted
AGP	<---	GIN	H4	.076*	.041	1.879	.080	.05	Accepted

The results of the indirect effects test also reveal the mediating role of Supply Chain Sustainability (SCC) in the relationships between the independent variables and the Adoption of Green Production (AGP). Energy Use Reduction (ERD) and Farmer Green Values (FGV) both exhibit partial mediation through SCC. It underscores significant indirect effects (β = 0.046, ***p* < 0.001**; β = 0.025, **p < 0.01**, respectively). This highlights that SCC strengthens the impact of these variables on AGP. Green Innovative Intentions (GIN) also shows partial mediation via SCC (β = 0.023, **p < 0.01**). It depicts that SCC enhances the influence of innovation on green practices. Conversely, AI Capability (AIC) demonstrates full mediation (β = 0.022, $p < 0.05$). It showed that its impact on AGP depends on SCC entirely. These findings underscore the important role of SCC in facilitating sustainable practices and enhancing the effects of key drivers such as ERD, FGV, AIC, and GIN. Details are provided in the following table 7:

Table 7

Indirect effects test results

		Confidence intervals				
Relationship	β	Lower bound	Upper bound	Beta	Sig.	Conclusion
ERD --> SCC --> AGP	0.046	0.018	0.089	0.045***	0.001	PM
FGV --> SCC --> AGP	0.025	0.008	0.057	0.027**	0.006	PM
AIC --> SCC --> AGP	0.022	0.008	0.051	0.024*	0.011	FM
GIN --> SCC --> AGP	0.023	0.008	0.053	0.024**	0.010	PM

PM= partial mediation, FM= full mediation

Table 8 demonstrates the results of the moderation analysis. It examines the role of Eco-Innovation (ECI) as a moderator in the relationship between SCC and AGP. In Model 1, SCC significantly predicts AGP ($\beta = 0.468$, $p < 0.01$). However, ECI has a negative direct effect on AGP ($\beta = -0.130$, $p < 0.001$) as shown in Table 8. Model 2 includes the interaction term (SCC*ECI). It depicts a negligible change in R^2 ($\Delta R^2 = 0.0002$). It depicts that the interaction effect is not significant. This indicates that ECI does not significantly moderate the association between SCC and AGP. Despite the strong influence of SCC on AGP, the moderating role of ECI appears to be limited. It underscores its direct rather than interactive impact on the adoption of green production.

Table 8

Moderation analysis test results

Dependent Variable is AGP	Model 1 (β)	Model 2 (β)
ECI	-.130***	-2.499**
SCC	.468**	9.146***
R2	.234	
SCC*ECI		.885
R2		.236
Change in R2		0.0002
F- Value	44.456	29.876

5. Discussion

This study focuses on determining the impact of FGV, AIC, GIN and ERD on AGP. Furthermore, the researcher also explored the mediation of SCC and the moderation of ENI in this process. For this purpose, data was gathered from 294 farmers/ employees working in ACCP projects.

The findings highlighted that AIC has an insignificant impact on AGP. This is due to the decreased implementation of AI technology in Pakistan's agriculture sector. Therefore, different agreements are signed between China and Pakistan under ACCP to promote the integration of AI technology in Pakistan's agricultural sector. This approach can also be beneficial for developing important AIC among the associated farmers. Although AI is effective in providing significant potential regarding operational efficiencies and decision-making (Kaggwa et al., 2024; Vaid & Sharma, 2022), limited focus has been given to its implementation in Pakistan's agricultural sector. Therefore, its association with green production might be hindered due to different environmental, social and economic factors. Consequently, it can also limit their influence concerning the adoption of green practices. Furthermore, the successful integration of AI also requires complex infrastructure systems as indicated by McMillan and Varga (2022). Therefore, to overcome this gap, ACCP has focused on integrating AI agricultural technology in Pakistan's agricultural sector.

In this study, farmer green values were also observed as a main driver of green production adoption. This is mainly because farmers who possess strong environmental beliefs and prioritize environmental preservation can be considered more convinced or motivated regarding the adoption of sustainable practices in their operations (Brown et al., 2021). These values can also play an important role in fostering a transformation towards eco-friendly methods (Rathnayake & Navaratne, 2022). Different eco-friendly methods can be included within this context such as organic farming (Panday et al., 2024). Moreover, renewable energy (Majeed et al., 2023) is also likely to play an important role in ensuring sustainability within the agricultural supply chain. Furthermore, farmers with strong green values can potentially act as role models within their communities. In this regard, they can promote collective AGP. These values align with global and local environmental policies. Consequently, it also further facilitates the implementation of sustainable production methods.

The findings of this study also show that green innovative intentions significantly contribute to the adoption of green production. This is because they reflect a proactive approach towards dealing with environmental challenges through creativity and innovation. In this regard, organisations or individuals who possess strong green innovative intentions are more likely to explore and implement novel solutions. It includes biodegradable packaging, renewable energy integration, or initiatives regarding waste recycling (Ballabh et al., 2022; Raźniewska, 2022). Although these processes are considered to be effective in promoting sustainable agriculture, however, important measures are also needed to be taken to manage energy consumption in the agriculture sector. In this regard, ERD has also resulted as a practical and impactful factor in driving green production. It encourages agricultural organisations so that they can adopt efficient practices that minimise the consumption of energy, reduce costs, and lower carbon footprints. This relationship is also underpinned by the growing awareness of the dual benefits of energy conservation such as environmental preservation and economic savings.

In addition, the mediating role of SCC underscored that AIC impacts green production only when it is effectively implemented. This shows that while AI provides advanced tools for the optimization of operations (Adesina et al., 2024), its potential can be effectively realised when it is integrated into such processes that foster sustainability. AI can support predictive analytics for the usage of resources (Donthireddy, 2024), and optimization of transportation routes (krishna Vaddy, 2023) so that the emissions can be minimized. However, their influence on green production adoption remains limited without the integration of these capabilities into a sustainable supply chain. This study has also shown that farmer green values are more impactful when they are supported by a sustainable supply chain. Within this context, farmers may adopt eco-friendly practices to ensure the implementation of SCC. The success of these practices often depends on the ability of the supply chain to support and sustain them.

Green innovative intentions also drive the adoption of green production particularly when these are combined with a sustainable supply chain. Although, innovative ideas are crucial for addressing environmental challenges (Ruziyeva & Ruziyeva, 2024). However, their practical implementation often depends on a strong supply chain. Similarly, energy use reduction results are significantly more effective in driving green production when these are supported by a sustainable supply chain. This underscores the interconnectedness of internal efforts for the conservation of energy and external systems that ensure these efforts are improved. The lack of significant moderation by eco-innovation showed that although eco-innovation is important. However, it may act more as an independent contributor to green production rather than refining the relationship between supply chain sustainability and green production. This highlights that the direct impact of eco-innovation can overshadow its role as a moderator.

Therefore, this study has been effective in emphasising the role of FGV, ERD, AIC and GIN in influencing AGP within the context of the agricultural sector in Pakistan. This emphasises the agricultural projects under ACCP to integrate advanced AI technology to improve their sustainable crop production, leading to the formulation and implementation of SCC. In this regard, the role of EIN is also inevitable. Thus, this study holds an effective base for future research within the context of sustainable agriculture.

6. Conclusion

Increased sustainability awareness among the consumers, has also encouraged different agricultural companies to take important measures to improve their AGP. These drivers include AIC, FGV, GIN, and ERD. The ACCP has also motivated the integration of AI technology in Pakistan's agricultural sector to improve its crop production and SCC. In this regard, the integration of eco-innovation is also considered to be vital. In addition to AIC, the role of FGV is also inevitable within the context of AGP. These values largely impact the overall implementation of technology and other sustainable practices in the agricultural sector to obtain a competitive advantage. Moreover, GIN among the farmers and associated employees also influence the AGP, emphasising the integration of SCC. This approach is also found to be crucial to achieving the required sustainable agricultural outcomes. Additionally, the agricultural sector in Pakistan is also taking important measures to integrate renewable energy for ERD, leading to the promotion of SCC. However, it was depicted that incorporating eco-innovative practices can further foster the effectiveness of efforts regarding sustainability within the agricultural sector. The study is important from both theoretical and practical perspectives.

For instance, this study has been effective in broadening the scope of the TOE framework within the context of AIC, FGV, GIN, ERD and AGP. This study has also tested the moderation of eco-innovation in association between SCC and AGP which adds novelty to this study. Moreover, the findings of this study can also encourage agricultural companies in Pakistan to integrate AI and other advanced technologies to collect real-time data for making sustainable and appropriate agricultural-related decisions.

6.1. Theoretical implications

This study effectively plays an important role in the theoretical understanding of green production adoption. It focuses on integrating multiple factors such as AIC, FGV, GIN, ERD, and SCC. The present study also enriches the growing body of literature as it focuses on evaluating the mediating role of SCC (Martins & Pato, 2019). Similarly, the moderating effect of ECI (Sumrin et al., 2021) has also been assessed in this study which is also a valuable contribution to literature. Theoretically, the study also provides a structure for understanding the association of various factors for fostering sustainable practices in the agriculture sector. The findings also enhance the theoretical information regarding the adoption of green practices in different developing economies (Rashid et al., 2024; Ruzzante et al., 2021) specifically in the context of agricultural firms in Pakistan. The findings provide an understanding of both technological and environmental factors. These factors play an important role in influencing different associated sustainable practices. Thus, this study ensures the provision of a valuable conceptual framework for future studies. Furthermore, the study highlights that there is an immense need to formulate a multi-dimensional approach regarding green production adoption, particularly in emerging economies such as Pakistan.

6.2. Practical implications

The present study also holds various practical implications and is effective in providing valuable insights for different stakeholders such as businesses, policymakers, and agricultural stakeholders. The study focuses on the importance of implementing AIC within agricultural operations. It also underscores the practical importance of fostering farmer-green values so that sustainability can be achieved (Gryshova et al., 2024). Additionally, the study also highlights the need for solidifying the supply chain sustainability and integration of ECI. In this way, the impact of green initiatives can be maximized. Practitioners can also focus on AI capabilities as key techniques for attaining efficiency and innovation in the processes of production (Svetlana et al., 2022). For agriculture firms, this research highlights that it is important to strengthen the supply chain sustainability so that the adoption of environmentally friendly practices can be fostered. This is because it acts as a key mediator in this process. Moreover, integrating eco-innovation into the supply chain can also boost the effectiveness of efforts related to green production. Policymakers should consider fostering such environments that encourage both technological advancements and eco-friendly initiatives. In this way, it can be ensured that agricultural firms in developing economies, particularly under frameworks like CPEC have access to the resources and support which is critical for ensuring sustainable development.

6.3. Policy recommendations

This study has been pivotal in providing important policy recommendations to promote AGP in Pakistan to improve its agriculture sector. In this regard, the government of Pakistan can focus on developing a regulatory framework for promoting AIC, ECI and other advanced technologies to promote green agriculture in Pakistan, leading to the sustainable development of the nation. This will be beneficial for Pakistan's agriculture sector to attain a competitive advantage, improving its overall green image at the global level. Additionally, different policies can also be formulated to encourage green agricultural joint ventures between China and Pakistan. This can be beneficial in increasing the economic growth of Pakistan.

7. Limitations and future research indications

While the present study provides valuable insights regarding the adoption of green production in the agricultural sector, however, is not without limitations. The study focuses on a specific geographic region which is Pakistan. Similarly, the sample was also primarily comprised of agricultural firms within the CPEC framework. It may limit the generalizability of the findings to other regions or sectors. The data in this study was also cross-sectional. It meant that it studied the relationships between variables at a single point in time. It also limited the ability of the researcher to make causal inferences or track changes over time. Most importantly, the study predominantly used self-reported data from employees. It can also introduce response biases or inaccuracies, particularly in relation to subjective measures such as green values and eco-innovation intentions.

To mitigate these shortcomings, future research should expand the scope of this study. Future researchers should focus on including a broader range of agricultural firms across different regions and countries. It can allow future researchers to undertake a comparative analysis of the factors through which the adoption of green production can be enhanced globally. Moreover, future studies can also explore other factors such as the role of government policies and technological infrastructure so that green production can be promoted. Similarly, future researchers can also focus on exploring the challenges which the firms face commonly regarding the implementation of green practices. Moreover, it is recommended that future researchers undertake a deeper investigation regarding the interactions between external stakeholders. Consequently, a more detailed and holistic understanding of the process of adoption can be attained.

Declarations

Data Statement: Data will be available upon request.

Conflict of Interests/Disclosures: The authors declared no potential conflicts of interest w.r.t the research, authorship and/or publication of this article.

Grant Support & Financial Disclosures: Not Applicable

List of Abbreviations

AI	Artificial Intelligence
AGP	Adoption of Green Production
ERD	Energy Use Reduction
SCC	Supply Chain Sustainability
FGV	Farmer Green Values
AIC	AI Capability
ECI	Eco-Innovation
GIN	Green Innovation Intentions
TOE	Technological Organizational Environmental
CPEC	China-Pakistan Economic Corridor
GDP	Gross Domestic Product

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Appendix A

Measurement Items

"AI Capability

1. We have the capability for simulating human intelligence behaviour in making prediction of customer decisions.
2. We have the capability for developing human-inspired algorithms to predict customer behaviour.
3. We have the capability for developing devices to replicate human intelligence and other cognitive functions.
4. We have the capability for developing AI for learning (the acquisition of information and rules for using the information), reasoning (using rules to reach approximate or definite conclusions), and self-correction.

Farmer Green Values

1. I feel a personal obligation to do whatever I can to prevent environmental degradation.
2. I feel obliged to save the environment from degradation, regardless of what others do.
3. People like to do whatever they can to protect the environment from degradation.
4. I feel guilty when I contribute to environmental degradation.
5. I feel obliged to bear the environment and nature in mind in my daily behaviour.

Green Innovative Intentions

1. I plan to act in an environmentally friendly way.
2. I intend to show environmentally friendly behaviour at work.
3. I intend to show environmentally beneficial behaviour at work.

Energy Use Reduction

1. Energy consumption is necessary to be very efficient in manufacturing industries.
2. Eco-friendly technology should be used for the reduction of energy use.
3. Eco-friendly production should be used for the reduction of energy use.
4. Renewable energy sources are good options for manufacturing and sustainability.
5. I believe energy saving is important.
6. Energy consumption is necessary to be very efficient in manufacturing industries.
7. Eco-friendly technology should be used for the reduction of energy use.

Adoption of Green Production

1. I purchase low-toxic and low-residue pesticides.
2. I purchase new high-efficiency fertilizers.
3. I purchase organic fertilizer.
4. I dispense pesticides according to the instructions.
5. I implement the safety interval of pesticides.
6. I adopt the technology of formula fertilisation by soil testing.
7. I adopt the technology of green prevention and control.

8. I adopt the technology of water-saving irrigation.
9. I recycle or reuse agricultural film.
10. I adopt the technology of straw return.
11. I adopt environmentally friendly packaging for agricultural products or reuse packaging.

Supply Chain Sustainability

1. We focus on green purchasing.
2. We practice eco-design or design for the environment.
3. We focus on internal environmental management.
4. We consider customer cooperation for environmental concerns.
5. We emphasise on investment recovery.

Eco-Innovation

1. Organizational structure innovations in the development of new organisational and management practices support environmental strategy.
2. Process innovations are associated with the way that companies make their products or offer services.
3. Product innovations are related to the quality and functionality of the products.
4. Market innovations are created through communication channels with the customer, brand values and the positioning of the product."

(Table 4)

Factor loadings, normality, reliability and validity test results

Items	Loadings	CA	Skewness	Kurtosis	CR	AVE	MSV
AGP1	.696	.942	AGP1	-1.254	0.943	0.601	0.405
AGP2	.748		AGP2	-1.304			
AGP3	.732		AGP3	-1.230			
AGP4	.711		AGP4	-1.435			
AGP5	.717		AGP5	-1.350			
AGP6	.724		AGP6	-1.336			
AGP7	.739		AGP7	-1.327			
AGP8	.736		AGP8	-1.199			

AGP9	.743		AGP9	-1.217			
AGP10	.762		AGP10	-1.235			
AGP11	.731		AGP11	-1.214			
ERD1	.713	.933	-1.157	.654	0.935	0.672	0.405
ERD2	.747		-1.051	.048			
ERD3	.726		-1.050	.061			
ERD4	.751		-1.065	.139			
ERD5	.840		-1.204	.578			
ERD6	.828		-1.344	1.159			
ERD7	.803		-1.195	.589			
SCC1	.790	.923	-.831	-.664	0.927	0.719	0.927
SCC2	.854		-.941	-.310			
SCC3	.755		-.847	-.569			
SCC4	.860		-.947	-.244			
SCC5	.843		-.947	-.220			
FGV1	.743	.882	-1.277	.215	0.885	0.607	0.389
FGV2	.758		-1.544	1.206			
FGV3	.766		-1.378	.647			
FGV4	.746		-1.430	.817			
FGV5	.717		-1.508	1.072			
AIC1	.786	.882	-1.127	.203	0.883	0.653	0.192
AIC2	.817		-.910	-.528			
AIC3	.826		-.935	-.361			
AIC4	.838		-1.092	.116			
ECI1	.799	.848	-.652	-.788	0.848	0.583	0.077
ECI2	.853		-.556	-.857			
ECI3	.813		-.608	-.751			

ECI4	.800		-.568	-.904			
GIN1	.873	.865	-.588	-.597	0.865	0.681	0.079
GIN2	.845		-.604	-.580			
GIN3	.856		-.675	-.366			