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Land fragmentation and green farming: livelihood strategies and resource endowment in sustainable agriculture

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Land fragmentation poses a significant barrier to sustainable agricultural development by influencing farmers' willingness and ability to adopt green production practices. This study aims to examine how land fragmentation affects such adoption, with particular attention to the mediating role of livelihood strategies and the moderating effect of resource endowments. The study utilizes survey data from 650 farmers in the provinces of Khyber Pakhtunkhwa and Balochistan, Pakistan. To analyze the relationships, we employed ordinary least squares (OLS) regression, threshold effect models, as well as mediation and moderation effect models. The analysis reveals that land fragmentation generally constrains the adoption of green production practices. However, the relationship is non-linear, exhibiting an inverted U-shape: moderate fragmentation can initially facilitate green adoption, while excessive fragmentation hinders it. Furthermore, livelihood strategies mediate this relationship, and resource endowments play a significant positive moderating role. The effects also vary across farmer generations, indicating heterogeneous behavioral responses. The findings underscore the complex and dynamic influence of land fragmentation on green agricultural practices. Policymakers should focus on resource integration, land-use optimization, and support for diversified livelihood strategies to promote sustainable agricultural development.

KEYWORDS

land fragmentation, green production practices, threshold effects, livelihood strategies, resource endowments

1 Introduction

The rapid growth of the global population, changing living standards, and accelerated socioeconomic development have led to significant land-use changes, resulting in increased land fragmentation. This fragmentation reduces both land and labor productivity, thereby threatening agricultural sustainability (Chen et al., 2024). The challenge is particularly pronounced in developing countries, where weak agricultural management systems, poor infrastructure, and extreme land fragmentation not only increase the cost of agricultural production but also reduce the availability of high-quality farmland. These challenges undermine farmers' ability to sustain livelihoods and hinder efforts to diversify household income sources (Wang et al., 2022).

To address these challenge, promoting green development and advancing the green transformation of agricultural practices have become essential strategies to resolve structural imbalances in agricultural supply and improve sustainability outcomes (Horlings and Marsden, 2011). Historically, agricultural productivity gains have relied heavily on chemical inputs such as fertilizers and pesticides. While these inputs have contributed to food security, they have also degraded soil fertility and caused environmental pollution (Hossain et al., 2022), ultimately compromising long-term sustainability. In response to the dual pressures of environmental degradation and the demand for economic growth, global attention is shifting toward green agricultural development (Li et al., 2023). Sustainable farming practices such as integrated pest management, organic farming, conservation tillage, crop rotation, precision agriculture, and agroforestry are increasingly being promoted to reduce chemical dependence, improve soil health, and enhance biodiversity. As farmers' decisions are central to agricultural production, their adoption of green practices is crucial for transitioning from conventional to sustainable farming models (Zhang and Zhao, 2024). However, severe land fragmentation poses significant barriers to the implementation of such green practices, complicating this transition.

The traditional resource-intensive and environmentally harmful agricultural model is no longer viable (Dogaru et al., 2024). Consequently, a growing body of research has explored farmers' green production behavior from both theoretical and empirical perspectives (Xu et al., 2024; Li et al., 2024). Green production emphasizes "resource conservation, environmental friendliness, ecological preservation, and product safety" through a range of practices including protective tillage before planting, green technologies during cultivation, and sustainable land management after harvest (Li et al., 2020). Prior studies highlight multiple factors influencing green behavior, such as farmers' resource endowments, environmental attributes, and policy environments (Li et al., 2020). The scale of landholding also shapes production goals and input preferences, affecting willingness to adopt green technologies.

Moderate land consolidation can enhance production efficiency, reduce transaction costs, and promote environmentally friendly practices (Lu et al., 2018). However, land fragmentation complicates such scale-based strategies. Most studies argue that land fragmentation increases costs, decreases output, reduces land-use efficiency, and impedes the adoption of modern technologies, thereby constraining sustainable agricultural development (Wang et al., 2023; Paul and wa Gĩthĩnji, 2018). In contrast, some scholars suggest that fragmentation can promote crop diversification, labor flexibility, and risk mitigation in monoculture systems (Lu et al., 2019; Manjunatha et al., 2013). Others identify a complex, nonlinear relationship between land fragmentation and production efficiency, influenced by crop types and farmers' off-farm employment (Sui et al., 2022).

Despite progress in understanding land fragmentation and agricultural practices, several important gaps remain. The relationship between varying degrees of land fragmentation and farmers' adoption of green production behavior is still unclear. Moreover, the underlying mechanisms, threshold effects, and contextual factors influencing this relationship have not been fully explored. Particularly, little research has examined how livelihood strategies mediate this relationship or how farmers' resource endowments (human, economic, and social capital) might moderate the effects of fragmentation. Addressing these gaps is crucial for designing effective policies to promote sustainable agricultural development in fragmented land contexts.

This study fills important gaps in the literature by analyzing how land fragmentation affects smallholder farmers' adoption of green production practices in Pakistan's Khyber Pakhtunkhwa and Balochistan provinces. Drawing on survey data collected in 2023, the research employs threshold effect models, along with mediation and moderation analyses, to explore the nonlinear impact of land fragmentation. It further examines the mediating role of livelihood strategies, the moderating influence of farmers' resource endowments, and variations across generations. This research is particularly important as it provides a nuanced understanding of the challenges land fragmentation poses to sustainable agriculture an increasingly urgent issue in developing regions. In addressing these issues, the study seeks to answer key research questions: How does land fragmentation influence farmers' adoption of green production practices? Is there a nonlinear (threshold) relationship between land fragmentation and green agricultural behavior? Do livelihood strategies mediate the relationship between land fragmentation and green production practices? And do farmers' resource endowments such as land quality, financial investment, and access to technical services moderate this relationship? By integrating multiple analytical approaches, the study offers practical insights for policymakers and development agencies aiming to promote green farming in contexts of fragmented landholdings.

The remainder of the paper is structured as follows: Section 2 reviews the empirical literature; Section 3 presents the theoretical framework and hypotheses; Section 4 outlines the research methodology; Section 5 discusses the results; Section 6 provides the analysis and interpretation; and Section 7 concludes with a summary and policy recommendations.

2 Literature review

Research on land fragmentation and sustainable agriculture explores how the fragmentation of land ownership affects farmers' ability to adopt eco-friendly practices and increase productivity. Fragmentation, particularly prevalent in developing countries, limits economies of scale and makes efficient use of inputs more challenging. Smaller, dispersed holdings require more labor, increasing costs and straining farmers' resources, which in turn hinders their ability to invest in and adopt green technologies. This disjointed land structure complicates sustainability efforts by limiting practices such as resource conservation, organic farming, and quality assurance that are critical to increasing agricultural resilience and environmental health (Rahman and Rahman, 2009; Tan et al., 2010).

Historically, agricultural development has relied heavily on chemical fertilizers and pesticides to increase food production, but over time, this approach has led to environmental degradation and worsening soil health (Tilman et al., 2002; Matson et al., 1997). In response, sustainable agriculture has gained momentum, with green production technologies becoming viable alternatives. These technologies aim to reduce reliance on hazardous inputs and increase environmental responsibility through methods such as waste reduction, ecological monitoring, and resource-saving agricultural practices (Pretty et al., 2018). However, the shift to green agriculture is often fragmented and inconsistent, creating structural challenges that growers must address to achieve truly sustainable farming systems.

The study highlights the critical role of land ownership size in influencing the adoption of green farming practices. Moderate land expansion can streamline operations, reduce transaction costs, and increase the efficiency needed to implement environmentally sustainable practices (Giang et al., 2019; Kadigi et al., 2017). Conversely, excessive land fragmentation increases operating costs, complicates technology adoption, and hinders the transition to modern agricultural methods (Su et al., 2024). Nonetheless, smaller plots offer unique advantages, such as supporting crop diversification, reducing risk, and increasing labor adaptability (Tan et al., 2006; Wang et al., 2020). For instance, small-scale systems enable farmers to efficiently adjust their labor allocation, select crops suitable for different soil conditions, and avoid the risks of monocultures a flexibility that could prove valuable in areas vulnerable to climate change or market fluctuations (Di Falco and Chavas, 2009).

The complex relationship between land fragmentation and green agriculture follows a non-linear pattern, with evidence that an initial increase in fragmentation can lead to positive outcomes. However, beyond a certain threshold, these benefits diminish, forming an inverted "U"-shaped association (Qiu et al., 2020). This suggests that the level of fragmentation influences green adoption behavior, with an optimal scope of fragmentation supporting sustainable practices. However, exceeding this range can lead to inefficiencies and undermine economies of scale, ultimately hindering the adoption of green practices by increasing operational challenges and reducing resource efficiency (Su et al., 2024).

Further investigation revealed that farmers' adoption of green practices is largely influenced by their livelihood strategies, resource availability, and support policies. Livelihood strategies, especially those that incorporate off-farm employment, can provide supplementary income, thereby reducing farmers' reliance on intensive land use and promoting the adoption of sustainable practices. Furthermore, resource endowments, including financial capital, credit access, and machinery ownership, play a crucial role in overcoming the challenges posed by land fragmentation. These resources enable farmers to invest in sustainable technologies, optimize operations on dispersed plots, and ultimately reduce costs associated with dispersed land management (Marenya and Barrett, 2007; Feyisa, 2020).

The literature highlights the need for a deeper exploration of how land fragmentation affects green agricultural practices, particularly through livelihood strategies and resource endowments that may amplify or mitigate these effects. Specifically, research should aim to clarify how the impact of fragmentation on sustainable practices shifts from beneficial to harmful. This study addresses these gaps by examining the complex, non-linear effects of fragmentation on green practices in the Khyber Pakhtunkhwa and Balochistan provinces of Pakistan. With this focus, it provides actionable insights into optimizing farmer behavior toward sustainable development, even amid structural barriers such as fragmented land ownership. These findings not only enhance our understanding of promoting green agriculture adoption but also highlight the importance of integrated land use planning and resource support. These strategies are critical to achieving sustainable agriculture and ensuring that farmers can balance productivity with ecological responsibility in areas where land fragmentation is common.

3 Theoretical framework and hypothesis

3.1 Land fragmentation and farmers' green production behavior

Farmers, as rational economic agents, aim to maximize profit in agricultural production (Li et al., 2023). In Pakistan, small-scale farming is prevalent, leading to significant land fragmentation. This fragmentation increases input costs, reduces labor productivity, and impedes economies of scale, limiting farmers' adoption of green production behaviors (Hussain et al., 2022; Malik et al., 2016). Mechanized operations, such as deep plowing and straw returning, are challenging on fragmented plots, and many fail to meet the scale requirements for agricultural social services, further restricting green farming practices. Additionally, fragmentation may psychologically reduce farmers' motivation to engage in green practices by weakening the incentive effects of policy subsidies.

> *H1:* Land fragmentation significantly inhibits farmers' adoption of green production behaviors.

However, land fragmentation also has positive effects, such as diversifying crops and enhancing soil fertility through crop rotation (Shah et al., 2021). As living standards improve, farmers become more conscious of food safety, and fragmented plots allow them to allocate portions of land for household consumption, thereby fostering the adoption of green production practices for personal use. According to multi-objective utility theory, farmers' production goals include maximizing profits, reducing risks, and minimizing labor. When land fragmentation is low and farmland concentrated, farmers prioritize economies of scale, often avoiding riskier green methods (Bayram et al., 2024). Moderate fragmentation may increase the likelihood of green adoption (Wang et al., 2023; Zhang et al., 2022). Conversely, in highly fragmented plots, the labor demands of green production deter farmers from improving green practices (Green et al., 2005). This suggests that land fragmentation creates varied behavioral responses among farmers, and its impact cannot be generalized.

> *H2:* There is a threshold effect in the relationship between land fragmentation and farmers' green production behavior, which follows an inverted U-shaped curve, initially increasing green behavior but decreasing as fragmentation intensifies.

3.2 Land fragmentation, livelihood strategies, and farmers' green production behavior

Livelihood strategies, a core component of the sustainable livelihood framework, reflect how individuals or households utilize their available resources to meet livelihood goals. In Pakistan, income disparities between agricultural and non-agricultural sectors have driven many farmers toward non-agricultural employment. When land is consolidated and of high quality, farmers are less likely to pursue non-agricultural livelihoods (Iqbal et al., 2021). However, high fragmentation pushes farmers toward non-agricultural income sources to maintain financial stability. These livelihood strategies influence production decisions (Huang et al., 2022). Farmers focused on agriculture are more market-dependent and motivated to produce high-quality green products to meet consumer demands. In contrast, those with non-agricultural strategies have reduced reliance on farming and are less inclined to adopt green practices.

> *H3:* Land fragmentation affects farmers' green production behavior by influencing their livelihood strategies.

3.3 Moderating effect of endowment

According to the rational small farmer theory, farmers' production choices are shaped by their available endowments. The better endowed a farmer is in land quality, capital, and technology, the more likely they are to adopt green production (Han et al., 2023). Green farming often requires advanced techniques and higher investments; sufficient financial resources can help overcome these barriers (Khan et al., 2022). Moreover, modern agricultural facilities and technical support enable farmers to manage fragmented land effectively and implement environmentally friendly methods (Khan et al., 2021; Khan et al., 2022).

> *H4:* Endowments moderate the relationship between land fragmentation and green production behavior. The stronger the endowments, the stronger the positive impact, and the weaker the negative impact of land fragmentation on green adoption.

4 Methodology

4.1 Study area and data collection

Khyber Pakhtunkhwa (KP) and Balochistan are two provinces in Pakistan with diverse topographical and agricultural features. KP, characterized by its mountainous terrain and the Hindu Kush range, is a major cereal-producing region. In contrast, Balochistan, the largest province by land area, has a sparse population and is known for its diverse landscapes and agricultural significance. Both provinces play vital roles in Pakistan's agricultural economy KP excels in cereal crops, while Balochistan contributes through agriculture, tourism, and its strategic border location (Tunio et al., 2024).

In 2023, a field survey was conducted to assess the relationship between land fragmentation and green farming practices. Data were collected from 650 farmers using a multistage random sampling approach. The research focused on understanding farmers' livelihood strategies, resource endowments, and their capacity to manage fragmented land while adopting sustainable practices. The sampling followed seven phases. First, Pakistan was selected as the country of study. Then, KP and Balochistan were chosen as representative provinces. Five districts were selected from each province based on their agricultural importance. Subsequently, ten tehsils, twenty union councils (UCs), and twenty villages were chosen. Structured questionnaires and face-to-face interviews were used to collect data from selected farmers. A pre-tested questionnaire was used to gather detailed information on socioeconomic characteristics, land ownership, farming practices, and challenges related to land fragmentation. After data collection, responses were edited, coded, and analyzed using Stata 14 to ensure accuracy and consistency. This rigorous process helped minimize bias and enhance data reliability.

The final sample size of 650 farmers was determined using Yamane (1973) formula for a homogeneous population:

$$n = \frac{N}{1 + N\left(e^2\right)} \tag{1}$$

Where Equation 1:
"n" = sample size.
"N" = population size (24,100 farmers).
"e" = precision level (5%).

This formula ensured representativeness and provided a robust foundation for statistical analysis of land fragmentation and green production practices in KP and Balochistan.

4.2 Variable selection

Dependent Variable: Farmers' Green Production Behavior. This study measures green production behavior based on four key agricultural practices: the adoption of water-saving technologies, the use of organic fertilizers, straw returning to the field, and the recycling of agricultural film. The total number of these practices adopted by each farmer is summed to generate a green production index, which serves as the dependent variable.

Independent Variable: Land Fragmentation. Following Hofman and Ho (2012) approach, land fragmentation is measured as the ratio of the number of cultivated land plots to the total cultivated area. A higher value reflects a greater degree of fragmentation.

Mediating Variable: Livelihood Strategy. Based on the classification of livelihood strategies by Hao et al. (2015) and considering the characteristics of the study area, the proportion of non-agricultural income to total income is used to measure the farmers' livelihood strategy status. A higher proportion indicates a higher degree of non-agricultural livelihood strategy.

Moderating Variable: Endowment. Farmers' agricultural production endowments are categorized into three dimensions: land quality, financial investment, and technical services. Land quality is measured by the area of high-standard farmland owned by the household (in hectares). Financial investment is captured by the total amount invested in agricultural production, with the natural logarithm applied. Technical services refer to access to green production technologies or services at the village level, measured as a binary variable indicating whether such services were received. These variables collectively represent the moderating role of endowment in influencing green production behavior.

Control Variables: To enhance the robustness of the regression results, individual characteristics, household characteristics, and village characteristics of the farmers are selected as control variables. Table 1 presents the variables and definitions.

4.3 Model specification

Baseline Regression: Since the dependent variable is ordinal, the ordinary least squares (OLS) method is used to construct the baseline

TABLE 1 Variable definitions.

Variable name	Definition and values
Dependent variables	
Green production behavior	Degree of adoption of green production practices (0 = Not adopted, 1 = Adopted)
Water-saving technology adoption	Adoption of water-saving technology (1 = Yes, 0 = No)
Organic fertilizer application	Use of organic fertilizer (1 = Yes, 0 = No)
Straw return to field	Practice of returning straw to the field (1 = Yes, 0 = No)
Agricultural film recycling	Recycling of agricultural film (1 = Yes, 0 = No)
Independent variables	
Land fragmentation	Number of cultivated land plots divided by total cultivated area (Hectare)
Mediator variables	
Livelihood strategy	The proportion of non-farm income relative to total household income (%)
Moderator variables	
Land quality	Area of high-standard farmland (Hectare)
Investment	Log of total investment in agricultural production
Technical services	Receipt of green production technology or services (1 = Received, 0 = Not received)
Control variables	
Gender	Gender of household head (1 = Male, 0 = Female)
Age	Age of household head (years)
Education	Education of household head (years)
Household size	Number of members in the household
Cultivated land area	Total area of cultivated land owned by the household (Hectare)
Land transfer area	Total area of land transferred in or out by the household (Hectare)
Farming in the next 5 Years	Intention to continue farming in the next 5 years (1 = Yes, 0 = No)
Cooperative membership	Membership in a cooperative (1 = Member, 0 = Non-member)
Neighbor support intensity	Number of neighbors who could provide 5,000 PKR in an emergency
Village regulations enforcement	Strength of village regulations enforcement (1 = Very weak, 5 = Very strong)

Source: Author's survey data.

regression model to examine the impact of land fragmentation on farmers' green production behavior (Tian and Wu, 2024):

$$Y_i = c_0 + c_1 X_i + c_2 C_i + \varepsilon_i \tag{2}$$

Where the Equation 2 Y_i is the dependent variable representing the degree of farmers' green production behavior adoption; X_i is the core independent variable representing land fragmentation; C_i represents a series of control variables that may affect the degree of farmers' green production behavior adoption; c_0 is the constant term; c_1 and c_2 are parameters to be estimated; and ε_i is the random disturbance term.

Threshold Effect Model: According to the theoretical analysis, the impact of different degrees of land fragmentation on farmers' green production behavior may not be constant. The threshold effect method was proposed by Hansen (2000) to avoid estimation bias caused by subjective threshold selection. Based on the research hypothesis, the green production behavior of farmers is taken as the dependent variable, and land fragmentation is treated as both the core independent variable and threshold variable to construct the threshold regression model:

$$Y_i = \mu_0 + \mu_1 X_i + \mu_2 C_i + \varepsilon_i, X_i \le \gamma \tag{3}$$

$$Y_i = \tau_0 + \tau_1 X_i + \tau_2 C_i + \varepsilon_i, X_i > \gamma \tag{4}$$

Where the Equation 3 Y_i, X_i, and C_i have the same meanings as above, and X_i also serves as the threshold variable with threshold value γ. If at least one γ value exists, the regression coefficient of land fragmentation on farmers' green production behavior is significantly different in different threshold intervals. This indicates the presence of a threshold effect. Based on this, the threshold value γ is estimated using OLS, and the samples are divided into groups according to γ to test the differences in the impact of land fragmentation on farmers' green production behavior in different groups. μ_0 and τ_0 are constants; μ_1, μ_2, τ_1, and τ_2 are parameters to be estimated; and ε_i is the random disturbance term.

Mediating Effect Model: To test the path through which land fragmentation affects farmers' green production behavior, the mediating effect analysis method by Wen et al. (2005) is used to construct the mediating effect model:

$$M_i = a_0 + a_1 X_i + a_2 C_i + \varepsilon_i \tag{5}$$

$$Y_i = b_0 + c' X_i + b_1 M_i + b_2 C_i + \varepsilon_i \tag{6}$$

Where Equation 4 analyses the impact of the core independent variable on the mediating variable, and Equation 5 analyses the impact of both the core independent variable and the mediating variable on the dependent variable. Here, Y_i, X_i, and C_i have the same meanings as above; M_i is the mediating variable representing farmers' livelihood strategies; a_0 and b_0 are constants; a_1, a_2, b_1, b_2, and c' are parameters to be estimated; and ε_i is the random disturbance term in Equation 6.

Moderating Effect Model: Referring to the research by Hu et al. (2024) interaction terms between land fragmentation and endowments are introduced. The regression analysis with interaction terms is conducted as follows:

$$Y_i = \theta_0 + \theta_1 X_i + \theta_2 Q_i + \theta_3 X_i \times Q_i + \theta_4 C_i + \varepsilon_i \quad (7)$$

$$Y_i = \omega_0 + \omega_1 X_i + \omega_2 I_i + \omega_3 X_i \times I_i + \omega_4 C_i + \varepsilon_i \quad (8)$$

$$Y_i = \delta_0 + \delta_1 X_i + \delta_2 T_i + \delta_3 X_i \times T_i + \delta_4 C_i + \varepsilon_i \quad (9)$$

Where, Equation 7, Y_i, X_i, and C_i have the same meanings as above; Q_i, I_i, and T_i represent the moderating variables of land quality, financial investment, and technical services, respectively in Equation 8; $X_i \times Q_i$, $X_i \times I_i$, and $X_i \times T_i$ represent the interaction terms between land fragmentation and land quality, financial investment, and technical services, respectively; θ_0, ω_0, and δ_0 are constants; θ_1 to θ_4, ω_1 to ω_4, and δ_1 to δ_4 are parameters to be estimated; and ε_i is the random disturbance term in Equation 9. The OLS regression is employed in this study due to its simplicity and effectiveness in estimating the linear relationship between land fragmentation and green production behavior. While OLS has limitations in addressing potential endogeneity and spatial dependence, the inclusion of control variables, such as farmers' socioeconomic characteristics, resource endowments, and livelihood strategies, helps mitigate omitted variable bias. Additionally, robustness checks, including alternative model specifications, ensure the reliability of the findings.

5 Results

5.1 Overview of descriptive statistics

TABLE 2 Definitions and descriptive statistics of variables.

Variable name	Mean (S. D.)	Min (Max)
Green production behavior (range 0–1)	0.599 (0.730)	0.094 (0.353)
Water-saving technology (Binary Yes = 1, No = 0)	0.129 (0.320)	0.000 (1.000)
Straw return to field (Binary Yes = 1, No = 0)	0.319 (0.461)	0.017 (1.000)
Organic fertilizer application (Binary Yes = 1, No = 0)	0.124 (0.330)	0.017 (1.000)
Agricultural film recycling (Binary Yes = 1, No = 0)	0.052 (0.222)	0.004 (1.000)
Land fragmentation (Plots per hectare)	1.539 (1.499)	1.000 (6.000)
Land quality (Hectares of high-standard farmland)	1.107 (1.289)	0.200 (7.400)
Livelihood strategy (% of non-farm income)	70.785 (36.823)	11.100 (100.0)
Technical services (Binary Received = 1, Not = 0)	0.466 (0.497)	0.000 (1.000)
Investment (Log of PKR)	6.121 (2.701)	0.000 (21.000)
Gender (Binary Male = 1, Female = 0)	0.967 (0.192)	0.000 (1.000)
Age (Years)	60.269 (9.161)	20 (89)
Education (Years of schooling)	6.560 (3.377)	0 (16)
Family size (Members)	4.477 (1.984)	1 (19)
Land transfer area (Hectares)	0.396 (1.480)	0.018 (5.000)
Cultivated land area (Hectares)	4.540 (7.115)	0.100 (16.000)
Farming in next 5 Years (Binary Yes = 1, No = 0)	0.709 (0.449)	0.000 (1.000)
Neighbor support intensity (Number of neighbors)	2.588 (1.380)	0.1 (10)
Cooperative membership (Binary Member = 1, Non-member = 0)	0.061 (0.247)	0.000 (1.000)
Village regulation enforcement (Ordinal scale 1 = weak, 5 = strong)	1.577 (0.985)	1 (5)

Source: Author's survey data.

Table 2 presents the descriptive statistics, offering valuable insights into green production behaviors and associated factors among rural households. The adoption rates of water-saving technology at 12.9% and organic fertilizer at 12.4% are relatively low, suggesting that while these practices are recognized as beneficial, their implementation remains limited. In contrast, the adoption rate of straw return to the field 31.9% is significantly higher, whereas agricultural film recycling is adopted by only 5.2% of households. These differences likely reflect varying levels of awareness, accessibility, and perceived practicality of the respective green practices. Land fragmentation, averaging 1.5 plots per hectare, indicates moderate fragmentation, which may hinder agricultural efficiency. Households show a strong reliance on non-farm income, which accounts for 70.7% of total income. This highlights the importance of supplementary income sources and suggests that such income could influence households' capacity to invest in environmentally friendly agricultural technologies.

The average age of respondents is 60.27 years, suggesting that older farmers play a dominant role in the sector. Older farmers typically possess more experience, which can be advantageous for managing risks and evaluating the utility of green practices. However, their risk aversion may make them more conservative in adopting innovations compared to younger farmers. Access to high-standard farmland is limited, with an average of 1.1 hectares per household, and only 46.6% of households report receiving green production technologies or services, indicating disparities in resource allocation and institutional support. Cooperative membership remains low at 6.1%, and the average land transfer area is just 0.4 hectares, underscoring challenges in resource mobilization and land consolidation. Despite these constraints, a notable 70.9% of households express an intention to continue farming over the next five years, reflecting a strong commitment to agriculture. However, the average score for village regulation enforcement is only 1.5 on a 5-point scale, suggesting that weak institutional enforcement may pose barriers to effective policy implementation. Overall, these findings highlight the need for targeted interventions to promote the adoption of green practices, improve access to key resources and services, and strengthen institutional and community support systems to address the challenges faced by rural farming households.

5.2 Impact of land fragmentation on farmers' adoption of green production practices

The analysis begins with a check for multicollinearity, where all variance inflation factors (VIF) were below 10, indicating that the model is well-specified and free from significant multicollinearity issues. The baseline regression results are presented in Table 3. Model (1) examines the relationship between land fragmentation and farmers' green production behavior as a univariate analysis. Model (2) incorporates additional variables that could influence farmers' adoption of green practices. Model (3) extends the baseline regression by including a quadratic term for land fragmentation to explore potential non-linear effects. The results from Models (1) and (2) indicate that land fragmentation has a significant negative impact on the adoption of green production practices by farmers, confirming Hypothesis H1. Model (3) further reveals that the linear term of the land fragmentation coefficient is significantly positive, while the coefficient for the quadratic term is significantly negative.

This suggests an inverted U-shaped relationship between land fragmentation and the adoption of green production practices. Alternative variable and model approaches were employed to test the robustness of these findings. The dependent variable "level of green production adoption" was replaced with a binary indicator of "adoption of green production practices," and a Logit model was used for regression analysis. Additionally, an Ordered Probit model replaced the OLS model for robustness checks. Both methods confirmed that land fragmentation significantly negatively affects green production adoption, with coefficient estimates remaining consistent. This supports the robustness and reliability of the baseline regression results, validating Hypothesis H1. Moreover, an endogeneity test was performed using "the average land fragmentation of other farmers in the same village, excluding the farmer's land fragmentation" as an instrumental variable. The Hausman test did not show significant results, suggesting that the potential endogeneity of the explanatory variables does not significantly bias the model estimates.

5.3 Threshold effects of land fragmentation

A threshold effect model was employed to explore how varying degrees of land fragmentation affect farmers' adoption of green production practices. The results of the LM test indicate a threshold value of 11.450 with a Bootstrap *p*-value of 0.042, confirming the presence of a threshold effect in the sample data. The analysis revealed a significant threshold value of 1.430 in the land fragmentation index. Below this point, fragmentation appears to promote green agricultural practices likely by encouraging crop diversification and flexible land use. However, beyond this threshold, fragmentation leads to operational inefficiencies that discourage the adoption of sustainable methods.

5.3.1 Descriptive analysis of land fragmentation distribution

To contextualize the chosen threshold, we performed a descriptive analysis of the land fragmentation index and illustrated the distribution using a histogram (Figure 1). The results reveal a right-skewed distribution, with the majority of observations falling below the threshold value of 1.430. This distribution pattern validates the

TABLE 3 Benchmark regression results of the impact of land fragmentation on farmers' green production behavior.

Variable	Green production behavior					
Models	Model (1)		Model (2)		Model (3)	
Land fragmentation	−0.038**	0.016	−0.038***	0.015	0.131*	0.071
Land fragmentation squared	-	-	-	-	−0.032***	0.012
Gender	-	-	0.149	0.117	0.158	0.109
Age	-	-	−0.002	0.004	−0.002	0.004
Family size	-	-	0.013	0.016	0.013	0.015
Education level	-	-	0.003	0.010	0.004	0.010
Cooperative membership	-	-	0.341**	0.134	0.374**	0.131
Family land area	-	-	−0.004	0.003	−0.005*	0.003
Farming in the Next 5 Years	-	-	0.251***	0.063	0.256***	0.063
Neighborhood relationship intensity	-	-	−0.046**	0.022	−0.047**	0.022
Transferred land area	-	-	−0.038**	0.016	−0.040**	0.015
Village regulations	-	-	0.059*	0.031	0.057*	0.030
Constant	0.660***	0.042	0.479*	0.250	0.523*	0.239
R^2	0.013		0.080		0.090	

Source: Author's survey data. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$. Standard errors are in parentheses.

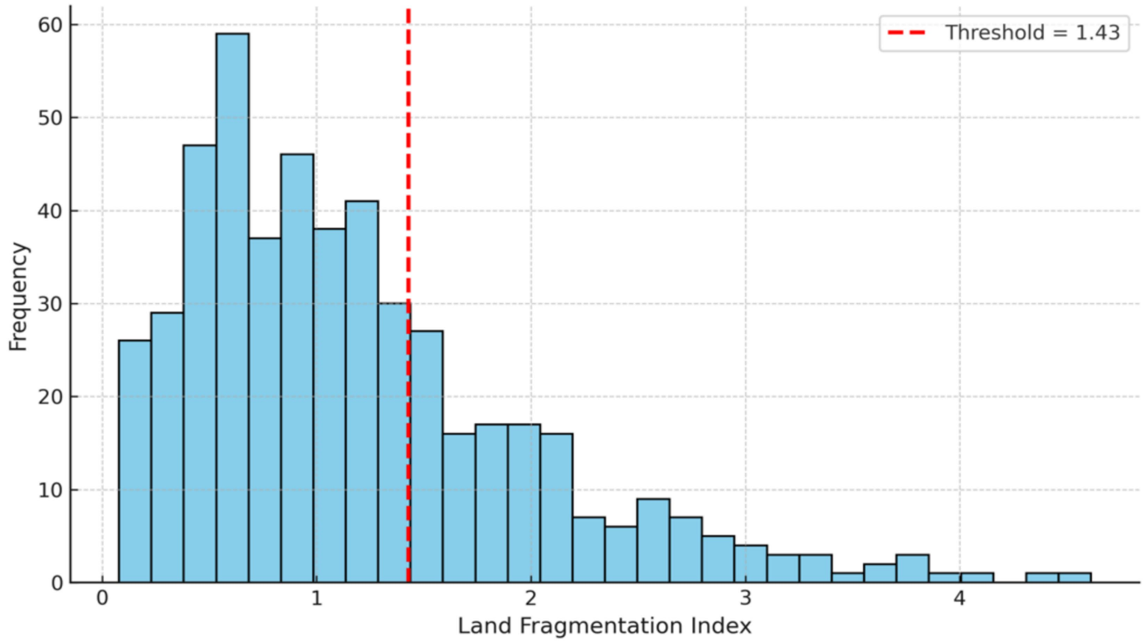

FIGURE 1
Histogram showing the distribution of land fragmentation. Source: Author's survey data.

TABLE 4 Land fragmentation threshold regression results.

Variables name	Green production practices							
	Low level of land fragmentation				High level of land fragmentation			
	Model (4)		Model (5)		Model (6)		Model (7)	
Land fragmentation	0.290**	0.121	0.445**	0.195	−0.040**	0.017	−0.120**	0.059
Control variables	-		-		-		-	
R^2 (Pseudo R^2)	0.120		0.065		0.109		0.069	

Source: Author's survey data. **denotes statistical significance.

threshold as a meaningful cutoff, distinguishing between relatively lower and higher levels of land fragmentation. Most farmers in the study area fall below this threshold, consistent with prevailing landholding patterns, where older farmers who often rely on traditional and less efficient farming practices predominate.

5.3.2 Threshold regression analysis

Based on this threshold, the sample data were divided into two groups, with the regression results shown in Table 4. Models (4) and (6) report the coefficients from the threshold regression (OLS), while Models (5) and (7) provide results from the probit model for robustness after segmenting the full sample according to the threshold value. For instance, in the OLS results, when land fragmentation is below 1.430, an increase in fragmentation significantly promotes the adoption of green production practices. Conversely, when fragmentation exceeds 1.430, further increases in fragmentation hinder the adoption of these practices.

5.3.3 Analysis of green production behavior

To further analyze the threshold effect and the differing impacts on green production behavior before and after the threshold, this study used variables for per-acre pesticide and fertilizer use, taking their logarithms. The data were divided into two groups based on the land fragmentation threshold, and regression models for per-acre pesticide and fertilizer use were constructed, as shown in Table 5. When land fragmentation is below 1.430, increasing fragmentation encourages farmers to diversify their planting and allocate land for staple crops, reducing the per-acre use of pesticides and fertilizers. However, when land fragmentation exceeds the 1.430 threshold, the average marginal effects of per-acre pesticide and fertilizer use are 0.020 and 0.003, respectively, though these results are not statistically significant. These results indicate that at higher levels of fragmentation, farmers may increase pesticide and fertilizer use to compensate for the higher costs of labor on fragmented plots, thereby reducing the adoption of green production practices driven by profit motives.

5.4 Mediation effect testing

To further examine how land fragmentation influences green production behaviors, livelihood strategies were introduced as a

TABLE 5 Impact of land fragmentation on farmers' pesticide and fertilizer input per acre.

Variables name	Low level of land fragmentation				High level of land fragmentation			
	Pesticide input		Fertilizer input		Pesticide input		Fertilizer input	
	Model (8)		Model (9)		Model (10)		Model (11)	
Land fragmentation	−0.810***	0.350	−0.333*	0.169	0.020	0.058	0.003	0.002
Control variables	-		-		-		-	
R^2	0.161		0.115		0.151		0.179	

Source: Author's survey data. *** denotes statistical significance at the 1% level, * denotes statistical significance at the 10% level and R^2 indicates the goodness-of-fit for the models.

TABLE 6 Test results of mediation effects.

Variable name	Green production behavior		Livelihood strategy		Green production behavior	
	Model (12)		Model (13)		Model (14)	
Livelihood strategy			−0.002**	0.001		
Land fragmentation	−0.041*	0.022	1.979**	0.981	−0.034	0.022
Control variables	-		-		-	
Constant	0.605**	0.259	71.097***	12.436	0.745***	0.265
R^2	0.011		0.095		0.020	

Source: Author's survey data. Significance levels: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 7 Test results of moderating effects.

Variable name	Green production behavior					
	Model (15)		Model (16)		Model (17)	
Land fragmentation	−0.032*	0.015	−0.022*	0.012	−0.051***	0.015
Financial input	-	-	0.058***	0.012	-	-
Arable land quality	−0.0065	0.005	-	-	-	-
Technical services	-	-	-	-	−0.012	0.093
Arable land quality × land fragmentation	0.019**	0.013	-	-	-	-
Financial input × land fragmentation	-	-	0.010**	0.004	-	-
Technical services × land fragmentation	-	-	-	-	0.066*	0.046
Control variables	-		-		-	
Constant	0.521***	0.219	0.206***	0.059	0.529**	0.227
R^2	0.084		0.075		0.088	

Source: Author's survey data. Significance levels: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

mediating variable. The mediation analysis involved testing the relationship between land fragmentation and livelihood strategies, and then examining how both variables together affect green production behavior. The results, as shown in Table 6, indicate that livelihood strategies play a mediating role in the relationship between land fragmentation and green production practices. Specifically, as non-agricultural livelihood strategies become more prominent, the negative effect of land fragmentation on green production behavior becomes more pronounced. Further testing using the Bootstrap method confirmed the significance of the mediating effect, as the confidence interval did not include zero. This suggests that land fragmentation indirectly influences green production behavior by shaping household income strategies, particularly by pushing farmers toward off-farm employment, which reduces the focus and resources available for sustainable agricultural practices.

5.4.1 Moderation effect testing

To explore whether resource endowments influence the relationship between land fragmentation and green production behavior, interaction terms between land fragmentation and arable land quality, financial input, and technical services were introduced into the regression models. The analysis presented in Table 7 shows that land fragmentation has a negative impact on green production behavior. However, the interaction terms are significantly positive, indicating that endowment factors moderate this relationship. Specifically, higher levels of land quality, greater financial investment, and the availability of technical services weaken the negative effect of land fragmentation. These results suggest that well-endowed farmers are better positioned to manage fragmented plots efficiently and adopt sustainable practices. The findings highlight the importance of strengthening agricultural resources and services to mitigate the adverse effects of fragmented land on green agricultural practices.

TABLE 8 Impact of land fragmentation and livelihood strategies on green production behavior across generations.

Variable name	Old generation of farmers				New generation of farmers			
	livelihood strategies		Green production behavior		Green production behavior		Green production behavior	
	Model 1		Model 2		Model 3		Model 4	
Land fragmentation	2.811**	1.401	−0.0357	0.030	−0.031	0.027	−0.042**	0.016
Livelihood strategy	-	-	-	-	−0.003*	0.002	-	-
Control	Yes		Yes		Yes		Yes	
Constant	84.718***	28.905	0.619***	0.063	0.929**	0.402	0.250	0.469
R^2	0.129		0.097		0.080		0.090	

Source: Author's survey data. Significance levels: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 9 Results of heterogeneity analysis on the impact of land fragmentation on different green production practices.

Variable name	Technology-intensive green production practices					
	Overall sample		New generation farmers		Older generation farmers	
Land fragmentation	−0.025**	0.009	−0.033*	0.019	−0.020	0.015
Control variables	-		-		-	
Constant term	0.550***	0.187	0.945***	0.350	0.584	0.414
R^2	0.059		0.070		0.065	

Variable name	Labor-intensive green production practices					
	Overall sample		New generation farmers		Older generation farmers	
Land fragmentation	−0.012	0.009	0.002	0.020	−0.020***	0.009
Control variables	-		-		-	
Constant term	0.002	0.126	−0.026	0.301	−0.335	0.252
R^2	0.039		0.070		0.049	

Source: Author's survey data. Significance levels: *$p < 0.05$; **$p < 0.01$, ***$p < 0.001$.

5.5 Heterogeneity analysis

The study further examined how generational differences influence the relationship between land fragmentation and green production behavior. Results in Table 8 show that land fragmentation significantly inhibits green production behavior among older farmers, while the effect is statistically insignificant for younger farmers. This pattern suggests that older farmers, who are generally more dependent on farming for their livelihoods and have less access to labor-saving technologies, may struggle more with the operational challenges caused by land fragmentation. In contrast, younger farmers, often engaged in non-farm employment and less reliant on agricultural income, are less affected by fragmentation when making decisions about adopting green practices. The mediating role of livelihood strategies remains valid among older farmers, indicating that their income diversification plays a role in moderating the relationship. Moreover, the study explored the impacts of land fragmentation on different types of green practices categorized into labor-intensive and technology-intensive practices. The results in Table 9 indicate that land fragmentation more strongly inhibits the adoption of technology-intensive practices compared to labor-intensive ones. Among older farmers, labor-intensive practices are more negatively affected, while among younger farmers, technology-intensive practices are more constrained. These findings emphasize that policy interventions should consider generational differences when promoting sustainable agriculture. Tailored support strategies such as providing technical assistance to older farmers and facilitating technology access for younger farmers could help enhance the overall adoption of green production practices across different demographic groups.

Agricultural green production behaviors are diverse. Based on production characteristics, organic fertilizer application, and film recycling are classified as labor-intensive green production behaviors, while water-saving technologies and straw returning are categorized as technology-intensive green production behaviors. To explore how land fragmentation affects the adoption of these different green production behaviors across generations, the overall sample is further segmented by generational differences. The results are shown in Table 9. Overall, land fragmentation significantly suppresses the adoption of technology-intensive green production behaviors more than labor-intensive ones. It also affects the labor-intensive green production behaviors of the older generation and the technology-intensive green production behaviors of the younger generation. This may be because the older generation adheres to traditional agricultural practices and tends to increase land productivity by investing more labor. In contrast, the younger generation, who primarily engage in non-farm employment, are more likely to use agricultural social services to replace labor inputs with higher opportunity costs. Consequently, their technology-intensive green production behaviors are constrained by fragmented plots' technical and cost effects.

6 Discussion

This study provides empirical evidence of the complex relationship between land fragmentation and farmers' adoption of green production practices, contributing to the growing body of literature on sustainable agriculture and land tenure dynamics. The findings reveal an inverted U-shaped relationship, indicating that while moderate land fragmentation can encourage the adoption of green farming techniques, excessive fragmentation creates substantial barriers to sustainable agricultural development. This nuanced perspective advances current understanding by highlighting a threshold effect rather than a simple linear relationship, consistent with emerging research on land use patterns and environmental outcomes (Xu et al., 2016). One key insight is that land fragmentation initially facilitates green production practices by fostering farm diversification, enhancing risk distribution, and encouraging sustainable land use strategies. These mechanisms have been documented by various scholars who find that smaller, diversified plots can reduce the risk of crop failure and promote environmentally friendly techniques such as integrated pest management and organic fertilization (He et al., 2019; Shah and Wu, 2019). Moderate fragmentation often supports crop rotation and intercropping, which are well-known sustainable agricultural practices (Weißhuhn et al., 2017). However, as fragmentation intensifies, it disrupts farm operations, increases transaction and management costs, and limits the efficient allocation of inputs, thus discouraging the adoption of green practices. This negative impact aligns with findings by Hao et al. (2023) and Chi et al. (2022), who emphasize the diminishing returns of fragmentation on farm productivity and technology uptake due to coordination difficulties and labor inefficiencies.

The observed threshold effect suggests that policy interventions aimed at land consolidation should balance the benefits of diversification with the need to reduce excessive fragmentation. This echoes policy discussions in rural development contexts emphasizing "optimal plot size" for sustainable intensification (Fao, 2019). The mediating role of livelihood strategies in shaping green practice adoption is in line with Huang et al. (2022), who find that off-farm employment reduces farmers' engagement with environmentally sustainable activities by diverting labor and financial resources away from farming. This dual livelihood perspective is critical, as it highlights how rural households balance economic security with environmental stewardship (Ellis, 2000). Moreover, livelihood diversification itself can be a risk management strategy, but may simultaneously reduce incentives for adopting practices that require sustained labor and capital investment (Deininger and Olinto, 2001). This study also underscores the moderating effects of resource endowments such as land quality, financial capital, and access to technical support on mitigating the negative impacts of fragmentation. Sui and Gao (2023) similarly report that resource availability cushions farmers from land constraints by enabling access to inputs and knowledge critical for green technology adoption. This finding resonates with broader agricultural innovation system literature emphasizing that financial and institutional support structures are vital for overcoming adoption barriers (Campuzano et al., 2023).

Generational differences further shape adoption behavior, with younger farmers demonstrating greater adaptability to fragmented land structures through the use of modern farming techniques and technologies (Nigussie et al., 2017). This generational effect echoes study by Pretty et al. (2011), which highlight the role of education, risk tolerance, and openness to innovation among younger farmers in driving sustainable agriculture transitions. In contrast, older farmers, often reliant on traditional knowledge and practices, may require targeted training and support to overcome barriers to green production.

Despite the statistical significance of our results, the relatively low explanatory power (R^2 generally under 0.1) reflects the inherent complexity of modeling farmer behavior in smallholder contexts. Such outcomes are common due to the multifaceted influences of socio-economic, cultural, institutional, and psychological factors that are difficult to fully capture quantitatively (Marenya and Barrett, 2007). Possible omitted variables include access to extension services, local environmental regulations, market conditions, social norms, and intrinsic motivations such as environmental awareness or risk attitudes (Feyisa, 2020). The inclusion of these dimensions could enhance future model performance. The cross-sectional nature of our data limits causal inference and the ability to observe behavioral dynamics over time, a limitation shared by many adoption studies (Pickles and Davies, 1989). Longitudinal or panel data approaches would better capture the evolution of adoption decisions in response to changing land and livelihood conditions (Gebru et al., 2021). Additionally, while we use instrumental variables to address endogeneity, further validation using natural experiments or randomized controlled trials would strengthen causal claims (Duflo et al., 2007).

In line with Feyisa (2020), our findings emphasize that adoption decisions extend beyond economic rationality to include factors such as access to advisory services, social capital, and perceived sustainability benefits. Future research should integrate qualitative approaches to explore farmers' attitudes, knowledge systems, and community engagement, which are critical to understanding and supporting sustainable agricultural transitions (Šūmane et al., 2018). In conclusion, this study provides a comprehensive understanding of how land fragmentation interacts with livelihood strategies and resource endowments to shape the adoption of green production practices. The inverted U-shaped relationship and the role of mediators and moderators offer valuable insights for designing policies that promote sustainable land use and rural development. Supporting farmers with diversified livelihood options, improved access to resources and services, and targeted generational interventions will be key to optimizing green practices in fragmented land systems.

7 Conclusion

This study contributes to the growing body of research on land fragmentation and sustainable agriculture by demonstrating that its effects on green production practices are non-linear. While moderate fragmentation can enhance adoption, excessive fragmentation eventually impedes sustainable farming methods. These findings underscore the importance of contextual factors, such as livelihood strategies, resource endowments, and generational differences, in shaping agricultural sustainability. By identifying the threshold where fragmentation transitions from beneficial to detrimental, this research informs optimal land use strategies. It highlights the need for balanced land management policies that promote sustainable agricultural practices while mitigating excessive fragmentation's adverse effects. Furthermore, the study advocates for integrated policy approaches considering economic, environmental, and social dimensions to foster resilient farming systems.

First, policies should be tailored to address land fragmentation's challenges at different levels. For smallholders, promoting precision agriculture and integrated land management strategies can optimize land use and productivity. For larger farms, encouraging intensive, technology-driven farming can mitigate fragmentation's negative impacts. Second, supporting resource integration is crucial. Investments in standardized farmland development, financial incentives for green farming, and enhanced technical training can help farmers overcome fragmentation constraints. Expanding social services to support farmers transitioning to non-farm employment can also enhance household resilience. Third, addressing generational differences in agriculture is essential. Younger farmers should receive financial and technical support to adopt advanced agricultural technologies, while older farmers should benefit from rural knowledge-sharing networks and practical training. Strengthening intergenerational learning can promote the diffusion of sustainable farming techniques and improve agricultural efficiency. Finally, future research should employ panel data to capture long-term changes in land fragmentation's impact on green production behaviors. Longitudinal studies can provide deeper insights into trends in fertilizer and pesticide use, biodiversity conservation, and soil management. Such research will refine land management policies and advance sustainable agricultural development strategies.

While this study provides valuable insights, some limitations exist. The cross-sectional data restricts long-term analysis, and future research should use panel data to track changes over time. Additionally, the relatively low R^2 values suggest that other factors, such as institutional support and market access, may influence green production behavior. Expanding the model with these variables could improve explanatory power. Lastly, as the study focuses on Pakistan, findings may not be directly generalizable to other regions. Comparative studies could enhance the broader applicability of these results.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

GD: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LL: Conceptualization, Funding acquisition, Investigation, Supervision, Visualization, Writing – review & editing. YX: Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. ZH: Formal analysis, Methodology, Project administration, Writing – review & editing. RT: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. NK: Conceptualization, Data curation, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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