frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 20 October 2025
DOI 10.3389/fsufs.2025.1599644

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OPEN ACCESS

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RECEIVED 25 March 2025
ACCEPTED 07 October 2025
PUBLISHED 20 October 2025

CITATION
Tunio RA, Lufeng L, Das G, Khan N and Gopang AA (2025) Mitigating land fragmentation: the role of organizational integration in promoting green technology adoption among farmers. *Front. Sustain. Food Syst.* 9:1599644. doi: 10.3389/fsufs.2025.1599644

Mitigating land fragmentation: the role of organizational integration in promoting green technology adoption among farmers

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Introduction: Land fragmentation remains a critical barrier to sustainable agriculture, as it reduces efficiency and hinders the adoption of modern green technologies, particularly in smallholder farming systems.
Purpose: This study explores the impact of land fragmentation on farmers' adoption of green technologies and examines how organizational integration can moderate these adverse effects.
Methods: Primary data were collected from 420 crop farmers across four districts of Balochistan, Pakistan. A binary probit model was employed to analyze the effects of land fragmentation and organizational integration on adoption behavior, with controls for education, training participation, land characteristics, and household factors.
Results: The findings reveal that land fragmentation significantly decreases the likelihood of adopting green technologies, while organizational integration strongly promotes adoption and offsets the negative effects of fragmentation. Moreover, education, participation in training, and machinery acquisition positively influence adoption, whereas high dependence on agricultural income, land transfer, and risk perception serve as barriers.
Conclusion: Policies that encourage land consolidation and strengthen cooperative networks are essential. Promoting organizational integration through farmer cooperatives can alleviate the constraints of fragmented farmland, enhance sustainable agricultural practices, and improve rural livelihoods.

KEYWORDS

land fragmentation, green technology adoption, organizational integration, sustainable agriculture, policy implications

1 Introduction

The agricultural sector stands at a critical juncture, grappling with pressing challenges such as climate change, rising food demands, and the imperative for sustainable practices (Abubakar et al., 2023). In this context, the adoption of green technologies is essential for fostering sustainable agricultural development, enhancing productivity, and addressing the environmental impacts associated with conventional farming (Qayyum et al., 2023; Khan et al., 2024; Lestari and Sunyoto, 2023). Green technologies, which include practices such as organic farming, biopesticide use, and precision agriculture, offer innovative solutions to improve resource efficiency, reduce chemical dependency, and promote ecological balance. However, despite their transformative potential, the adoption of these technologies among farmers remains limited, particularly in regions where land fragmentation hinders agricultural progress. Land fragmentation, a prevalent issue in many agricultural systems, refers to the division of farmland into multiple, often non-contiguous plots (Ntihinyurwa and de Vries, 2020; DeLay et al., 2022). This division arises from various factors, including historical land reforms, population pressures, and economic transitions. Such fragmentation significantly complicates the efficient management of agricultural resources, thereby impeding the adoption of modern farming technologies. For instance, in Pakistan, approximately 60% of cultivated land is fragmented, predominantly managed by smallholder farmers struggling to achieve economies of scale (Kousar et al., 2020; Elahi et al., 2020).

Fragmented farmland poses substantial barriers to the adoption of green technologies. Existing literature highlights how fragmentation elevates operational costs, reduces resource-use efficiency, and undermines economies of scale (Songoro, 2020). Furthermore, the scattered nature of landholdings constrains farmers' ability to invest in costly green technologies, often due to limited resources or restricted access to credit facilities. The complex relationship between land fragmentation and green technology adoption has garnered considerable attention in academic research (Chi et al., 2022). While some scholars argue that fragmentation discourages sustainable practices by increasing transaction costs and complicating land management (Jumani et al., 2020), others suggest that, under certain circumstances, fragmented holdings may encourage farmers to adopt innovative practices to maximize productivity across diverse plots (Chi et al., 2022). This duality highlights the need for a nuanced understanding of the factors influencing green technology adoption in fragmented agricultural landscapes. In Pakistan, the complexities of land tenure systems shaped by cultural and socio-economic factors further complicate this relationship. Smallholder farmers frequently face critical decisions, choosing between traditional farming methods and experimenting with modern technologies (Malik et al., 2016; Nisar et al., 2020).

Amidst these challenges, organizational integration has emerged as a vital component in facilitating the adoption of green technologies among farmers. Organizational integration, which refers to the collaborative relationships formed within cooperatives or farmer associations, can help mitigate the adverse effects of land fragmentation. By pooling resources, sharing knowledge, and enhancing access to training, these integrated structures enable farmers to navigate the constraints associated with fragmented land holdings. Research indicates that farmers engaged in cooperative systems are more likely to adopt sustainable practices, as these organizations provide essential support, including training on new technologies, access to credit, and collective bargaining power in the market (Dong et al., 2023; Luo et al., 2022; Ma et al., 2022; Galdeano-Gómez et al., 2006). In Pakistan, the establishment of agricultural cooperatives has demonstrated significant potential in advancing modern farming practices among smallholders, enabling collective investment in green technologies and securing access to lucrative markets (Khan et al., 2022; Jabbar et al., 2022). A study conducted by Khan et al. (2022) and Geffersa (2024) found that cooperative membership significantly increased the adoption of organic farming practices among farmers, primarily through shared resources and collective learning.

The indispensable role of social capital in agricultural settings cannot be overlooked, as it often determines the success of organizational integration. Social capital is defined as the networks, relationships, and norms that facilitate cooperation among individuals and groups (Putnam, 2000). In rural areas, social capital plays a crucial role in fostering trust and collaboration among farmers, enhancing their capacity to adopt green technologies (Usman and Ahmad, 2018). Farmers embedded in robust social networks are more inclined to participate in cooperatives, exchange knowledge on sustainable practices, and collectively negotiate for favorable input prices (Abid et al., 2017; Sheikh et al., 2015). Furthermore, institutional awareness programs and active local organizations amplify farmer's understanding of available green technologies, enabling informed decisions that advance sustainable agricultural practices.

This study seeks to empirically examine the interplay between land fragmentation, organizational integration, and the adoption of green technologies among crop farmers in Balochistan, Pakistan. While the findings focus on this specific region, they offer critical insights applicable to other areas in Pakistan characterized by fragmented land and smallholder farming systems. Drawing on survey data from 420 farmers across four districts of Balochistan, this research employs a binary probit model to analyze how land fragmentation impacts the adoption of green technologies. Additionally, the study explores how organizational integration alleviates the constraints posed by fragmented land holdings. By exploring these dynamics, the findings aim to expand the theoretical frameworks surrounding green technology adoption and provide actionable insights for policymakers seeking to enhance sustainable agricultural practices in fragmented landscapes.

In Pakistan, addressing land fragmentation through targeted government policies and cooperative promotion holds transformative potential for agricultural sustainability. Policies encouraging land consolidation, coupled with initiatives to strengthen cooperative networks, can create a supportive environment for farmers to adopt green technologies more effectively. For instance, government-supported training programs tailored for cooperative members can accelerate knowledge transfer on sustainable practices, enabling farmers to make informed decisions about technology adoption (Khan and Khan, 2018). Additionally, financial assistance directed at cooperative groups can help lower the barriers to entry for adopting expensive green technologies, allowing for greater participation in sustainable agriculture.

However, the relationship between land fragmentation and green technology adoption is complex and multifaceted, influenced by a variety of economic, informational, and institutional factors. Organizational integration through cooperatives offers a promising pathway for overcoming the challenges posed by fragmentation, enhancing the likelihood of farmers adopting sustainable practices. This study contributes to the existing body of literature by providing empirical evidence from Balochistan, elucidating the pivotal role that organizational integration plays in promoting green technology adoption among farmers operating in fragmented agricultural contexts. The insights gained provide actionable recommendations for agricultural policymakers in Pakistan, particularly for strengthening the operational capacity and technological adaptability of smallholder farmers. By comprehending the interplay between land fragmentation, organizational integration, and green technology adoption, policymakers can design strategic interventions that not only elevate farmers' livelihoods but also contribute to overarching goals of environmental sustainability, food security, and rural economic development. These findings underscore the urgent need for collaborative approaches to transform agriculture into a more resilient and sustainable sector globally.

The remainder of the paper is organized as follows: Section 2 outlines the theoretical framework and research hypotheses. Section 3 details the research methodology. Section 4 presents the results and offers a discussion of the findings. Finally, Section 5 concludes the study by summarizing key insights, discussing policy implications, and addressing its limitations.

2 Theoretical analysis and research hypotheses

2.1 The impact of land fragmentation on farmers' adoption of green technology

Land fragmentation is a significant characteristic of agricultural production. Generally, land fragmentation refers to a situation where a single farmer operates multiple, non-contiguous, and relatively small parcels of land (Bradfield et al., 2021). Existing studies have identified that the fundamental characteristics of land fragmentation can hinder farmers' adoption of green technologies in several ways. First, compared to large contiguous plots, fragmented land increases the labor input and costs associated with agricultural machinery due to the lack of connectivity between plots. This also results in increased time consumption and transportation costs for moving labor and agricultural inputs, which raises the costs associated with adopting green technology a phenomenon referred to as the "cost effect." Second, the adoption of green technology often requires farmers to invest in various agricultural machinery, such as soil testing equipment and unmanned aerial vehicles, to address their limited capacity for green production. However, rational choice dictates that land fragmentation restricts effective consolidation and scale operations, thus limiting investments in other necessary factors, which complicates the substitution of inputs needed for adopting green technology. This is termed the "substitution effect." Third, the land resources available to farmers determine their adoption and utilization rates of modern production technologies. Under the constraints of fragmented land and small plot sizes, farmers may find it challenging to reach the scale threshold required for adopting green technologies, resulting in a cost structure that cannot be effectively distributed. This ultimately limits their willingness and extent to adopt agricultural technologies, which is known as the "technology crowding-out effect." Based on this analysis, we propose the hypothesis H1:

H1: Land fragmentation negatively impacts farmers' adoption of green technology.

2.2 The impact of organizational integration on farmers' adoption of green technology

Numerous studies indicate that cooperatives, as a new type of agricultural operating entity, can facilitate the adoption of green technologies among farmers, primarily through the following mechanisms: First, joining a cooperative can help reduce the costs associated with adopting green technologies. Specifically, it lowers the search costs for acquiring technology, corrects cognitive biases regarding technology, and dismantles the barriers to applying new agricultural technologies, thereby enhancing accessibility. Additionally, cooperatives hold advantages in the supply of quality seeds and agricultural inputs, which can lower transaction costs for farmers (Lenaerts et al., 2022). Finally, cooperatives offer various social services, including agricultural machinery, labor assistance, sales, logistics, and financing, which can mitigate issues such as insufficient agricultural input supply and difficulties in selling products, ultimately reducing both input-output costs and market transaction costs (Zhang et al., 2023). Second, being part of a cooperative can increase the rate of green technology adoption among farmers (Tang et al., 2023). Cooperatives regularly provide training in technical methods and practices, and according to the theory of technology diffusion, such training is a crucial means of spreading agricultural technologies, significantly influencing farmers' adoption of green practices (Liu et al., 2022). Based on this rationale, we propose the hypothesis H2:

H2: Organizational integration positively influences farmers' adoption of green technology.

2.3 The moderating effect of organizational integration

According to classical economic theory, farmers are rational decision-makers whose adoption of green technologies is fundamentally based on a cost-benefit analysis. Therefore, farmers are likely to adopt green technologies only if the inputs and outputs meet their expected goals. As analyzed previously, when faced with decisions about adopting green technologies, farmers are influenced by three pathways of cost effects, substitution effects, and technology crowding-out effects stemming from land fragmentation, which may lower their willingness to adopt green technologies. However, compared to farmers who are not part of a cooperative, those who join can gain support in terms of agricultural information, technical services, input supply, and capital, which lowers the information and transaction costs associated with adopting green technologies. Moreover, they can benefit from social services provided by cooperatives, such as machinery, labor assistance, and financing, which help alleviate constraints related to labor resources and agricultural machinery configuration when adopting green technologies. Therefore, from this perspective, organizational integration can help mitigate the inhibiting effects of land fragmentation on farmers' adoption of green technologies. Based on this, we propose the hypothesis H3:

H3: Organizational integration positively moderates the inhibiting effect of land fragmentation on farmers' adoption of green technology.

3 Methodology

3.1 Data source

The data for this study originates from a survey conducted by the research team in December 2023, focusing on crop producers in Balochistan Province, Pakistan, a key agricultural region in this research. Balochistan is a major contributor to Pakistan's agricultural output, accounting for 4.63% of the national crop sowing area and 5.57% of total crop production in 2023. Its role in the country's food security makes it a critical area for studying the adoption of green technologies in agriculture. Given Balochistan's significance, this study investigates the adoption of green technologies among crop producers in the region, which is crucial for advancing sustainable agricultural practices and improving productivity. The survey covered four districts in Balochistan, with two tehsils randomly selected in each district. To ensure comprehensive and reliable data, in-depth one-on-one, in-home interviews were conducted between researchers and farmers. The data collected from these interviews, focusing on household characteristics, agricultural practices, and the uptake of green technologies, resulted in 420 valid responses. The wide scope of the survey makes the sample highly representative and reliable for drawing meaningful conclusions on the role of green technology adoption in enhancing agricultural sustainability.

3.2 Variable selection

3.2.1 Dependent variable

The dependent variable in this study is the adoption of green technology by farmers. Considering the actual production conditions in the survey areas, we represent farmers' adoption of green technologies through three dimensions: organic fertilizer, biological pesticides, and soil testing for tailored fertilization. A farmer is assigned a value of 1 if they adopt one or more of these green technologies; if not, the value is 0, resulting in a binary outcome ranging from 0 to 1. While this binary measure provides a clear indication of whether or not a farmer has adopted green technology, it simplifies the diversity and intensity of adoption behaviors. For example, adopting only one practice may not reflect the same level of engagement as adopting multiple practices. Due to data constraints, we are unable to construct a count or index variable, and thus our findings should be interpreted as reflecting basic adoption rather than adoption intensity. Nevertheless, the three selected technologies were chosen because they are the most widely promoted in Balochistan and are central to environmentally sustainable farming practices in the province, making them representative indicators of green technology adoption in this context.

3.2.2 Independent variables

The core independent variables include land fragmentation and organizational integration. Land fragmentation measures the actual fragmentation of farmland owned by farmers. The survey's agricultural operational characteristics section asked about the total area of farmland operated by farmers and the number of plots managed. Thus, we represent land fragmentation using the average number of (number of plots/farmed area). A higher average number of plots indicates greater fragmentation of land. Organizational integration is represented by whether farmers are managing or have joined a cooperative; if either condition is true, it is coded as 1, and if neither is true, it is coded as 0. While this measure is dichotomous, it captures farmers' formal links to collective action structures. In the Balochistan context, cooperatives provide a variety of services such as collective procurement of inputs, access to shared agricultural machinery, technical training, extension advice, pooled labor resources, and facilitation of sales and market access. These mechanisms not only reduce individual transaction costs and mitigate risks but also expand access to knowledge and markets. From a social capital perspective, organizational integration strengthens trust, information exchange, and norms of reciprocity among farmers, which lowers perceived risks and increases confidence in adopting new green technologies.

3.2.3 Control variables

To avoid estimation bias due to omitted variables, we draw on relevant studies to include control variables across five dimensions: individual characteristics of farmers, family endowment characteristics, operational characteristics, land endowment characteristics, and community traits. For individual characteristics, we control for age, educational level, political affiliation, and risk preference types. Regarding family endowment characteristics, we include variables such as the number of agricultural workers in the household, the proportion of agricultural income, whether agricultural insurance is purchased, and the status of machinery acquisition. For operational characteristics, we control for perceived technological risks, participation in agricultural training, and attitudes toward new agricultural technologies. The perceived technological risk is measured on a five-point scale in the survey, where "very small," "small," "average," "large," and "very large" are assigned values of 1–5. This study defines a perceived risk above 3 as high risk and 3 or below as low risk. For land endowment characteristics, we include farmland area, whether land has been transferred, and the state of agricultural infrastructure. Lastly, for community characteristics, we control for the development level of townships, terrain features, and the distance of farmland from the town. The inclusion of these control variables is important to account for heterogeneity in adoption decisions. For example, village terrain (plain vs. hilly) matters because flat land allows more efficient use of machinery and uniform application of fertilizers and biopesticides, while hilly terrain poses accessibility and cost challenges. Land transfer is included as tenure insecurity reduces farmers' incentives to invest in long-term or costly sustainable practices. Risk perception is also critical, since farmers who perceive higher technical or financial risks are more reluctant to adopt new technologies. Incorporating these variables ensures that the estimated effects of land fragmentation and organizational integration are not confounded by these contextual and behavioral factors. The variables' name and their definitions are presented in Table 1.

3.3 Model construction

This study primarily focuses on the impact of land fragmentation and organizational integration on the adoption of green technologies by farmers, and it discusses the moderating effect of organizational integration on land fragmentation. To this end, we establish the following econometric model for empirical testing:

$$Acc_i = \alpha_0 + \alpha_1 Fra_i + \alpha_2 Coo_i + \alpha_3 Control_i + \epsilon_1 i \tag{1}$$

Where the Equation 1 $\mathrm{Acc}_i = \alpha_0 + \alpha_1 \mathrm{Fra}_i + \alpha_2 \mathrm{Coo}_i + \alpha_3 \mathrm{Control}_i + \epsilon_{1i}$ aims to explore the adoption of green technology among farmers. In this model, Acc_i represents the level of green technology adoption by a specific farmer i. The variable Fra_i denotes the degree of land fragmentation experienced by that farmer, while Coo_i captures the organizational integration status. Additionally, $Control_i$ includes various control variables that may influence the farmer's decision to adopt green technology. The term ϵ_{1i} represents the error term, accounting for any unexplained variation in the model. This model is designed to empirically test the relationships between these factors, specifically examining how organizational integration might moderate the impact of land fragmentation on the adoption of green technology.

$$Acc_i = \beta_0 + \beta_1 Fra_i + \beta_2 Coo_i + \beta_3 (Fra_i \times Coo_i) + \beta_4 Control_i + \epsilon_2 i \tag{2}$$

In this model, i represents individual farmers, and Equation 2, *Acc* denotes the dependent variable of farmers' adoption of green technology. The variables *Fra, Coo, and Fra×Coo* represent the core independent variables of land fragmentation, organizational integration, and their interaction term, respectively. *Control* encompasses a series of control variables, while ϵ_1 and ϵ_2 are the random error terms for the two models. In Model (1), α_1 and α_2 capture the direct effects of land fragmentation and organizational integration on the adoption of green technology by farmers. Model (2) builds upon Model (1) by introducing the interaction term between land fragmentation and organizational integration to assess the moderating effect of organizational integration on land fragmentation. If β_1 is significantly negative and β_3 is significantly positive, it indicates that organizational integration can effectively alleviate the constraints posed by land fragmentation on farmers' adoption of green technology. Given that the dependent variable of farmers' green technology adoption is a binary discrete variable,

TABLE 1 Variable name and its definitions.

Variable name	Meaning and assignment
Dependent variable	
Farmers' adoption of green technology	Adopted = 1; not adopted = 0
Independent variable	
Land fragmentation	Number of plots/cultivated area (Hac)
Organizational integration	Joined = 1; not joined = 0
Individual characteristics	
Age	Actual age of the farmer (years)
Education level	Primary and below = 1; Junior high = 2; Senior high and above = 3
Political affiliation	Party member = 1; not a member = 0
Risk preference type	Risk-averse = 1; Risk-neutral = 2; Risk-seeking = 3
Family endowment characteristics	
Number of farming family members	Number of family members engaged in farming (people)
Proportion of agricultural income	Proportion of agricultural income to total family income (%)
Purchase of agricultural insurance	Yes = 1; no = 0
Agricultural machinery purchase status	Purchased machinery = 1; not purchased = 0
Production and management characteristics	
Perception of technical risk	High risk perception = 1; Low risk perception = 0
Participation in agricultural technology training	Participated = 1; not participated = 0
Attitude toward new agricultural technology	Not accepting = 1; neutral = 2; accepting once = 3
Land endowment characteristics	
Cultivated area	The logarithm of the actual cultivated area (hm^2)
Transfer of land	Yes = 1; no = 0
Status of agricultural infrastructure	Not complete = 1; not very complete = 2; complete = 3
Village and town characteristics	
Level of development of village	Extremely poor = 1; relatively backward = 2; medium = 3; relatively developed = 4; very developed = 5
Topography of village	Plain = 1; hilly = 2
Distance from agricultural land to city	Distance from home to the nearest town (km)

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TABLE 2 Definitions and descriptive statistical analysis of variables.

Variable name	Mean (S.D.)
Dependent variable	
Farmers' adoption of green technology	0.427 (0.495)
Core independent variable	
Land fragmentation	0.314 (0.310)
Organizational integration	0.368 (0.483)
Individual characteristics	
Age	55.427 (10.076)
Education level	2.028 (0.736)
Political affiliation	0.233 (0.423)
Risk preference type	1.648 (0.717)
Family endowment characteristics	
Number of farming family members	2.063 (0.696)
Proportion of agricultural income	0.468 (0.265)
Purchase of agricultural insurance	0.841 (0.366)
Agricultural machinery purchase status	0.671 (0.470)
Production and management characteristics	
Perception of technical risk	0.207 (0.406)
Participation in agricultural technology training	0.783 (0.413)
Attitude toward new agricultural technology	2.070 (0.493)
Land endowment characteristics	
Cultivated area	4.489 (1.724)
Transfer of land	0.841 (0.366)
Status of agricultural infrastructure	1.466 (0.605)
Village and town characteristics	
Village development level	3.399 (0.664)
Topography of village	1.091 (0.296)
Distance from agricultural land to city	4.251 (3.432)

the estimation will utilize a binary Probit model following a normal distribution.

4 Results and discussions

4.1 Descriptive statistical analysis

The results in Table 2 highlight several key factors influencing farmers' adoption of green technology. About 42.7% of farmers in the sample have adopted green technology, indicating moderate adoption rates. Organizational participation is relatively low, with only 36.8% of farmers involved in agricultural organizations, hinting at a potential gap in collective support for green technology. Farmers tend to be older, with an average age of 55.4 years, and most have education levels ranging from junior high to senior high. There is a notable inclination toward risk aversion and a strong tendency to seek agricultural training, as 78.3% have participated in technology training. Additionally, a high percentage of farmers have agricultural insurance (84.1%) and have transferred land (84.1%), reflecting a proactive approach to managing risks and optimizing land use. These insights underline the importance of individual, land-related, and organizational factors in shaping green technology adoption.

TABLE 3 Adoption rates of individual green technologies by farmers.

Measure	Adoption rate (%)	Non-adoption rate (%)
Organic fertilizers	25	76
Biological pesticides	13.2	87.9
Soil testing and formula fertilization	23.6	77.6

4.1.1 Adoption patterns of green technology among farmers

The data reveals a varied landscape in the adoption of green technology practices among farmers. The most frequently adopted measure is the use of organic fertilizers, with 25% of farmers reporting this practice. This is closely followed by soil testing and formula fertilization techniques, adopted by 23.6% of farmers. In contrast, the least commonly implemented practice is the use of biological pesticides, with only 13.2% of farmers choosing this method (Table 3). In terms of overall adoption, a significant 61.8% of farmers reported not using any form of green technology, suggesting limited interest or access. Among those who have embraced green practices, 29.1% adopted a single type of technology, while just 13.2% utilized two or more. These figures indicate that enthusiasm and engagement with green technology remain relatively low among farmers, pointing to potential barriers or gaps in motivation and support for sustainable agricultural practices.

4.1.2 Intergroup difference analysis

Before model estimation, the sample was divided into two groups based on whether farmers adopted green technology: the adopting group and the non-adopting group. An intergroup difference analysis was conducted to preliminarily assess the relationships between variables, with results shown in Table 4. There are significant differences between the two groups of farmers in terms of land fragmentation, organizational integration, age, educational level, political affiliation, number of farming household members, whether they purchase agricultural insurance, machinery acquisition status, participation in agricultural training, attitudes toward new agricultural technologies, farmland management scale, agricultural infrastructure conditions, and town development levels. Specifically, farmers who adopt green technology show significantly higher levels of organizational integration and lower degrees of land fragmentation compared to those who do not adopt green technology. This preliminary statistical analysis suggests that land fragmentation may inhibit farmers' adoption of green technology, while organizational integration may promote it. However, the specific effects require further empirical testing.

4.2 Baseline regression analysis

Before regression, the variance inflation factor (VIF) was used to test for multicollinearity among variables. The results indicated that the maximum VIF was 3.65, with a mean of 1.41, all below the critical value of 10. This suggests that multicollinearity is not a serious issue. Using Stata 17.0 software, a Probit model was established to estimate the econometric model (1) discussed earlier. To ensure the robustness of the results, robust standard errors were utilized, as shown in Table 5. Here, Model Probit (1) represents the direct impact of land fragmentation on farmers' adoption of green technology while controlling for other variables. Model Probit (2) indicates the direct effect of organizational integration on farmers' adoption of green technology, also while controlling for other variables. Model Probit (3) combines both land fragmentation and organizational integration to analyze their joint effects on farmers' adoption of green technology. The regression results show that the coefficients for core explanatory variables maintain consistent direction across different models, indicating the robustness and reliability of the estimates. A closer examination reveals three key effects.

4.2.1 Land fragmentation has a significant negative impact on farmers' adoption of green technology

In the regression results of Model Probit (1) and Model Probit (3), land fragmentation is significant at the 10% level, with a negative coefficient. This suggests that the more severe the land fragmentation, the lower the likelihood of farmers adopting green technology, thus confirming research hypothesis H1. The underlying reason is that as land fragmentation increases, farmers face higher agricultural production costs and greater barriers to adopting green technology, leading to lower willingness to adopt.

4.2.2 Organizational integration has a significant positive impact on farmers' adoption of green technology

In the regression results of Model Probit (2) and Model Probit (3), organizational integration is significant at the 5% level, with a positive coefficient. According to the sample statistics, the proportion of farmers adopting green technology among those who joined cooperatives is 58.23%, compared to only 33.58% among those who did not. This indicates that organizational integration promotes the adoption of green technology among farmers, thereby validating research hypothesis H2. The underlying mechanisms can be explained in several ways. Joining a cooperative facilitates access to resources and information that enhance farmers' ability to adopt new technologies. It can reduce the costs incurred by farmers in agricultural production, while the series of social services provided by cooperatives such as agricultural technical training, machinery services, collective procurement of inputs, and labor assistance can break down the technological and financial barriers to adoption and improve the accessibility of green technologies. Beyond these tangible services, cooperatives also foster social capital by strengthening trust, reciprocity, and information exchange among farmers. This collective environment reduces perceived risks, builds confidence in unfamiliar practices, and encourages knowledge sharing, which together help explain why cooperatives significantly increase the likelihood of adopting green technologies.

4.2.3 While control variables are not the main focus of this study, the estimation results are generally consistent with existing research conclusions

In the regression results of Model Probit (3), it can be observed that the coefficient for educational level is positive and passes the significance test at the 10% level, indicating that higher educational levels are associated with a greater likelihood of farmers adopting green technologies. Education enhances awareness of environmental benefits, information access, and the ability to understand and apply technical knowledge, which collectively foster adoption. The coefficient for the proportion of agricultural income is negative and passes the significance test at the 5% level, suggesting that as the proportion of agricultural income increases, farmers are less willing to adopt green technologies. This can be explained by the fact that a higher proportion of agricultural income means farmers face greater agricultural costs and risks, which, under these dual pressures, reduces the likelihood of adopting green technologies. The coefficient for agricultural machinery acquisition is positive and passes the significance test at the 10% level, indicating that farmers who have purchased agricultural machinery are more likely to adopt green technologies compared to those who have not. Mechanization lowers labor costs and simplifies the use of sustainable inputs, making adoption more feasible. The coefficient for perceived technical risk is negative and passes the significance test at the 10% level, suggesting that the greater the perceived technical risk, the less likely farmers are to adopt green technologies. This reflects behavioral hesitancy, as risk-averse farmers tend to avoid practices perceived as uncertain or costly.

The coefficient for participation in agricultural technical training is positive and passes the significance test at the 5% level, indicating that farmers who participate in technical training are more likely to engage in green technology practices compared to those who do not participate. Training reduces information barriers, improves confidence in new technologies, and facilitates peer learning. The coefficient for land transfer is negative and passes the significance test at the 10% level, indicating that as farmers transfer land, their likelihood of adopting green technologies decreases. This may be due to the instability of land rights caused by the duration of land transfer, which makes farmers reluctant to adopt green technologies on rented land where long-term returns are uncertain. The coefficient for the level of town development is positive and passes the significance test at the 10% level, indicating that the higher the level of town development, the greater the awareness of green technologies among farmers, thus increasing their likelihood of adoption. Better-developed areas

TABLE 4 Intergroup difference analysis of sample farmers.

Variable	Mean (non-adopters)	Mean (adopters)	Mean difference	T-value
Land Fragmentation	0.353	0.262	0.091	3.047***
Organizational integration	0.268	0.503	−0.234	−5.117***
Age	56.622	53.820	2.802	2.873***
Educational level	1.890	2.213	−0.323	−4.600***
Political affiliation	0.199	0.279	−0.080	−1.930*
Risk preference type	1.630	1.672	−0.042	−0.601
Number of farming household members	1.980	2.175	−0.195	−2.898***
Agricultural income ratio	0.469	0.467	0.002	0.085
Purchase of agricultural insurance	0.789	0.913	−0.124	−3.519***
Machinery acquisition status	0.602	0.765	−0.163	−3.609***
Perceived technological risks	0.224	0.186	0.038	0.953
Participation in agricultural training	0.703	0.891	−0.187	−4.771***
Attitude toward new agricultural technology	2.016	2.142	−0.126	−2.634***
Farmland management scale	4.173	4.915	−0.742	−4.509***
Land transfer status	0.821	0.869	−0.048	−1.338
Agricultural infrastructure status	1.423	1.525	−0.102	−1.728*
Village development level	3.350	3.464	−0.115	−1.776*
Village topography	1.085	1.098	−0.013	−0.450
Distance from agri-land to city	4.217	4.297	−0.080	−0.239

Significance levels are indicated as follows: $^{***}p < 0.01$, $^{*}p < 0.10$.

also provide stronger access to markets, extension services, and input supply chains, lowering barriers to adoption. Finally, the coefficient for village terrain is positive and passes the significance test at the 5% level, suggesting that flat areas are more conducive to farmers adopting green technologies compared to hilly areas. This is because plains are easier to cultivate using machinery and allow for more uniform application of fertilizers, pesticides, and irrigation, while hilly terrain increases operational complexity and costs. These findings are consistent with studies from Punjab and Sindh, where land fragmentation, tenancy, and cooperatives similarly shape adoption (Kousar et al., 2020; Khan et al., 2022; Jabbar et al., 2022). While provincial differences in infrastructure and resources exist, the mechanisms highlighted here education, cooperative participation, and land transfer are broadly relevant across Pakistan's smallholder systems.

4.3 Moderating effect analysis

The regression results (Table 6) show that organizational integration significantly offsets the negative influence of land fragmentation on green technology adoption. This highlights the importance of cooperatives not only as resource-pooling entities but also as mechanisms that reduce uncertainty and transaction costs in fragmented systems. Beyond providing shared machinery and inputs, cooperatives foster trust, reciprocity, and information exchange, consistent with social capital theory (Putnam, 2000; Usman and Ahmad, 2018). Similar findings from China (Dong et al., 2023), and Pakistan Khan et al. (2022) indicate that collective action enables farmers to overcome scale disadvantages and risk perceptions, thereby making sustainable practices more accessible. These results suggest that fragmentation alone does not determine adoption outcomes; institutional arrangements such as cooperatives can reshape incentives and capacities, making green practices viable even in fragmented settings. To test this moderating role, we applied a stepwise Probit model. Model Probit (4) examines the moderating effect of organizational integration without controls, while Models Probit (5) through (9) progressively add individual, household, production, land, and village-level characteristics. Across all specifications, land fragmentation remains significantly negative, while the interaction term between fragmentation and organizational integration is consistently positive and statistically significant. Moreover, as additional controls are introduced, the significance of the interaction term increases from the 10% to the 5% level, confirming the robustness of the moderating effect. These results support Hypothesis H3, demonstrating that organizational integration effectively alleviates the constraints of land fragmentation on farmers' adoption of green technologies.

4.4 Robustness check

To verify the reliability and stability of the estimation results presented earlier, a robustness check was conducted. Specifically, we replaced the binary Probit model with a binary Logit model as an

TABLE 5 Baseline regression results: effects of land fragmentation and organizational integration on green technology adoption (Binary Probit model).

Variable	Model (1): land fragmentation	Model (2): organizational integration	Model (3): both core variables
Land fragmentation	−0.507* (0.281)	–	−0.535* (0.288)
Organizational integration	–	0.347** (0.146)	0.358** (0.148)
Age	−0.003 (0.008)	−0.005 (0.008)	−0.006 (0.008)
Educational level	0.235** (0.107)	0.219** (0.108)	0.209* (0.108)
Political status	0.083 (0.166)	0.004 (0.170)	0.011 (0.171)
Risk preference	−0.042 (0.095)	−0.037 (0.095)	−0.037 (0.096)
Household farm labor	0.133 (0.102)	0.146 (0.102)	0.154 (0.103)
Agricultural income ratio	−0.734** (0.297)	−0.616** (0.295)	−0.715** (0.298)
Agricultural insurance	0.230 (0.207)	0.224 (0.211)	0.227 (0.209)
Machinery ownership	0.343** (0.164)	0.273* (0.163)	0.309* (0.164)
Technical risk perception	−0.283* (0.169)	−0.298* (0.169)	−0.287* (0.170)
Training participation	0.458** (0.184)	0.412** (0.186)	0.418** (0.185)
Attitude to new technology	0.233 (0.143)	0.220 (0.145)	0.222 (0.145)
Cultivated area (log)	0.136* (0.071)	0.136** (0.069)	0.093 (0.073)
Land transfer	−0.602** (0.259)	−0.494* (0.261)	−0.507* (0.261)
Infrastructure condition	0.128 (0.114)	0.103 (0.113)	0.124 (0.114)
Village development	0.178* (0.100)	0.167* (0.100)	0.174* (0.100)
Terrain (plain = 1)	0.520** (0.222)	0.394* (0.223)	0.488** (0.225)
Distance to city	0.001 (0.019)	−0.0004 (0.019)	−0.002 (0.019)
Constant	−2.917*** (0.909)	−2.877*** (0.923)	−2.635*** (0.927)
Sample size	429	429	429
Wald χ^2	66.93***	65.80***	73.57***
Pseudo R^2	0.131	0.134	0.142

Dependent variable = adoption of green technology (1 = adopted, 0 = not adopted). Robust standard errors in parentheses. ***, **, * = significance at 1%, 5%, and 10%.

alternative specification. The use of different model specifications helps ensure that the observed relationships between variables are not dependent on a particular functional form. Additionally, to account for potential heteroskedasticity in the error terms which could bias the standard errors and inference robust standard errors were applied in the estimation. This adjustment ensures that the reported significance levels are reliable even if the variance of the errors is not constant across observations. The results of the robustness check are summarized in Table 7. Comparing the Logit model outcomes with those from the Probit model shows that the coefficients of the core explanatory variables, such as land fragmentation and organizational integration, as well as the interaction term, remain consistent in direction and significance. Specifically, land fragmentation negatively affects green technology adoption, while organizational integration has a positive effect. The interaction between land fragmentation and organizational integration also retains its expected moderating effect. These findings confirm that the earlier empirical results are robust: the conclusions drawn from the Probit model remain valid even when using a Logit model and robust standard errors. This consistency strengthens the credibility of our analysis and supports the reliability of the observed effects.

5 Conclusions and policy implications

5.1 Conclusions

Based on survey data from 420 crop farmers in the Balochistan Province of Pakistan, this study used a binary Probit model to examine the effects of land fragmentation and organizational integration on farmers' adoption of green technology. The findings reveal that: (1) Land fragmentation has a significant inhibitory effect on the adoption of green technology by farmers; (2) organizational integration significantly promotes farmers' green technology adoption and positively moderates the inhibitory effect of land fragmentation; (3) Other factors also impact green technology adoption, including education level, agricultural income proportion, machinery acquisition, risk perception, training participation, land transfer, township development, and village terrain. Notably, education level, machinery acquisition, agricultural training, township development, and flat village terrain significantly enhance adoption, whereas a high proportion of agricultural income, risk perception, and land transfer pose significant barriers.

TABLE 6 Moderating effect of organizational integration on land fragmentation (Binary Probit estimates with stepwise controls).

Variable	Model (4): base	Model (5): + individual controls	Model (6): + household assets	Model (7): + production/ operations	Model (8): + land assets	Model (9): + village characteristics
Land fragmentation	−0.863* (0.456)	−0.732* (0.392)	−0.758* (0.391)	−0.734* (0.383)	−0.706* (0.375)	−0.819** (0.408)
Organizational integration	0.311 (0.215)	0.265 (0.205)	0.182 (0.209)	0.131 (0.209)	0.041 (0.209)	0.036 (0.212)
Land fragmentation × organizational integration	1.043* (0.626)	0.996* (0.576)	1.066* (0.576)	1.111* (0.571)	1.181** (0.549)	1.130** (0.578)
Constant	−0.152 (0.151)	−0.192 (0.548)	−0.880 (0.668)	−1.321* (0.769)	−1.463* (0.827)	−2.522*** (0.925)
Sample size	429	429	429	429	429	429
Wald χ^2	25.81***	41.37***	56.70***	55.10***	68.66***	74.56***
Pseudo R^2	0.062	0.083	0.111	0.129	0.139	0.150

Dependent variable = adoption of green technology (1 = adopted, 0 = not adopted). Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$. Each successive model incrementally adds controls: Model (5) = + individual characteristics; Model (6) = + household assets; Model (7) = + production/operations; Model (8) = + land assets; Model (9) = + village characteristics.

TABLE 7 Robustness check using Logit regression (alternative specification).

Variable	Model (1): land fragmentation	Model (2): + organizational integration	Model (3): both core variables	Model (4): with interaction
Land fragmentation	−0.830* (0.499)	−0.867* (0.525)	−1.482* (0.881)	–
Organizational integration	–	0.566** (0.242)	0.581** (0.246)	0.015 (0.365)
Land fragmentation × organizational integration	–	–	–	2.049* (1.095)
Control variables	Controlled	Controlled	Controlled	Controlled
Constant	−5.025*** (1.564)	−4.929*** (1.581)	−4.523*** (1.598)	−4.375*** (1.595)
Sample size	429	429	429	429
Wald χ^2	60.12***	59.67***	65.16***	65.23***
Pseudo R^2	0.132	0.136	0.142	0.151

Dependent variable = adoption of green technology (1 = adopted, 0 = not adopted). Robust standard errors in parentheses. ***, **, * = significance at 1%, 5%, and 10%.

5.2 Policy implications

Policies should address both structural and institutional barriers. First, farmland consolidation should be supported through clearer land rights, exchange markets, and subsidies for land transfer. These steps would reduce the constraints of fragmentation and create conditions for technology adoption. Second, cooperative development should be prioritized. Governments can strengthen cooperatives by providing subsidies, technical support, and extension services. Cooperatives can enhance access to inputs, machinery, labor, and training, while fostering trust and information exchange that reduce farmers' perceived risks. Models such as "family farm + cooperative" can further expand organizational integration and improve adoption of green practices.

5.3 Limitations and future research

While this study provides valuable insights into the interplay between land fragmentation, organizational integration, and green technology adoption, several limitations should be acknowledged. First, the binary measure of adoption simplifies behavior and may overlook differences in adoption intensity. Future studies should construct indices or count measures to capture the number and depth of practices adopted. Second, the cross-sectional design restricts causal inference; panel or longitudinal data would provide stronger evidence. Finally, as the analysis focuses on farmers in Balochistan, the findings should be generalized cautiously. Nevertheless, the mechanisms identified particularly the roles of education, cooperative participation, and land transfer are also observed in Punjab and Sindh, suggesting broader relevance across Pakistan's smallholder systems and, with care, to similar South Asian contexts. Future work could extend to multi-province or cross-country comparisons and incorporate additional factors such as institutional quality and social capital to provide a more comprehensive understanding of adoption dynamics.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

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

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The Project on Quality of Higher Education Talent Cultivation and Teaching Reform in Sichuan Province from 2024 to 2026 (JG2024-0948).

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.

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The author(s) declare that Gen AI was used in the creation of this manuscript. Since the authors are not native English speakers, they utilized Grammarly, QuillBot, and ChatGPT to enhance the grammar, fluency, and readability of this manuscript during its preparation. After using these tools, the authors thoroughly reviewed and edited the content as necessary and take full responsibility for the accuracy and integrity of the publication.

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