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Role of Institutional Factors in Multiple Sustainable Agricultural Practices: Evidence from Uzbekistan

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Land degradation is driving Uzbek farmers to strengthen their resilience by adopting sustainable agricultural practices. This study explores the nature of this adoption, focusing exclusively on biopesticides, crop rotation, and sustainable manure application among farmers in Uzbekistan. Using data from the UzFarmBarometer 2024 ($n = 1,225$), we employ a multivariate probit model that accounts for the potential interrelated nature of these practices. The results indicate that exposure to diverse agricultural training significantly increases the likelihood of both manure application and biopesticide use. Farmers' perceptions of decision-making autonomy have a strong positive influence on biopesticide adoption but negatively affect sustainable manure application. Perceptions of secure land tenure encourage the adoption of crop rotation and the use of manure. On the other hand, risk aversion consistently discourages the adoption of sustainable practices, while membership in agricultural clusters promotes sustainable manure application. Based on these findings, key policy priorities include expanding the diversity of agricultural training programs, enhancing farmers' decision-making autonomy, and providing land tenure security. These measures can help accelerate the adoption of sustainable practices and strengthen agricultural resilience in Uzbekistan and across the region.

Keywords: autonomy; biopesticide use; crop rotation; land tenure; manure application; training diversity

1. Introduction

Sustainable agriculture practices (SAPs) are increasingly recognized as vital for food security, natural resource preservation, and improving the resilience of rural communities. Essentially, using SAPs is crucial for reducing the impacts of climate change, improving soil health, and using water resources efficiently. The Food and Agriculture Organization (FAO) (2003) Committee on Agriculture proposed a framework for good agricultural practices that provides an insight into the scope and wide-ranging objectives of GAPs and defines it as practices that are socially acceptable and environmentally non-degrading. The framework identifies ten generic components of GAPs, including soil management, water management, crop and fodder production, crop protection, animal production, animal health and welfare, harvest and on-farm processing and storage, energy and waste management, human welfare, health and safety, and wildlife and landscape conservation.

As highlighted by Partey et al. (2018), SAPs contribute significantly to farm income and food security, particularly in vulnerable regions such as Northern Ghana, with findings that resonate with the challenges faced in Uzbekistan. Wang et al. (2019) state that a variety of social, institutional, and economic factors influence the methods that farmers choose to use. Numerous factors, including farmer attitudes, institutional incentives, and technology accessibility, affect the implementation of SAPs. Han and Niles (2023) propose an adoption spectrum paradigm that categorizes farmers based on their engagement with sustainable practices to offer a more thorough understanding of adoption dynamics. Bilal and Jaghdani (2024), who provide comparative analysis relevant to Central Asia, also look at the outcomes and difficulties of agricultural advances in Pakistan. From the institutional viewpoint, as noted by Kurbanov, Djanibekov, and Herzfeld (2025), most farms in Uzbekistan are bound by procurement policies that require them to designate significant portions of their land for specific crops to fulfill production quotas and sell their yields to state-owned enterprises, thereby restricting the decision-making autonomy of farms regarding crop diversification. Moreover, most of the knowledge platforms available to farms in Uzbekistan are layered in the network of government agencies, government-non-governmental organizations (GNGOs), and research institutes, as a result of the Soviet legacy. In this context, these institutions frequently neglect the actual knowledge requirements of farms and primarily operate in a top-down manner, according to Kurbanov et al. (2024). Likewise, in Uzbekistan, agricultural clusters are being actively developed, which serve specific functions of the state while also delivering essential resources to farms, including inputs, investments, and technology. However, as noted by Djanibekov, Herzfeld, and Petrick (2024), farms that are part of these agricultural clusters possess very limited negotiating power because the clusters create a situation of monopsony power that they can wield whenever needed.

This study is focused on Uzbekistan, specifically four regions namely: Samarkand, Andijan, Khorezm, and Kashkadarya, using the UzFarmBarometer data set of 2024. It attempts to identify the interlinkage of institutional, behavioral, and farm characteristic factors in adopting three sustainable agricultural practices namely: biopesticide use, crop rotation, and sustainable manure application in Uzbekistan. Considering the unique institutional setting in Uzbekistan and the ongoing reform agenda in the agriculture sector, the research study is largely formed by the following questions:

- What are the main institutional determinants of adopting SAPs?
- Is adoption of SAPs an independent or complementary strategy?

The current study's primary goal is to attempt to identify the institutional, socioeconomic, and behavioral elements that influence Uzbek farmers' decisions to simultaneously deploy

several sustainable practices. In our view, these methods fit into broader strategies to make agriculture more sustainable in addition to being good for the environment. The SAPs under research are usually more affordable and available to farmers than expensive technologies like sprinkler systems, drip irrigation, or land laser leveling. They do, however, require a supportive institutional structure and are highly knowledge-dependent, especially biopesticide use, as the latter requires proper knowledge, training, and experience in applying in the field. To this end, the FAO (2002) notes that organic manure use in Uzbekistan has significantly increased soil humus content, supporting the previous notion of soil health preservation. Similarly, Syromiatnykov et al. (2026) state that crop rotations incorporating legumes significantly improved grain yield and marketable output in Uzbekistan, supporting the narrative of Partey et al. (2018). With regard to biopesticide use, the FAO (2023) reports that it is a safer and more sustainable alternative to chemical pesticides, targeting only locusts and grasshoppers while posing no risk to human health or ecosystems.

To address these questions, we draw on cross-sectional farm-level data from the UzFarmBarometer project. Considering that farmers may adopt multiple sustainable agricultural practices simultaneously and these adoptions are likely to be interdependent, we use a multivariate probit (MVP) regression model. This approach is particularly relevant for studies that aim to examine both the individual- and joint-adoption decisions while exploring the association between institutional factors and the implication of sustainable practices.

2. Literature Review

The goal of the literature review is to provide a background on the use of SAPs in Uzbekistan's institutional setting and to highlight key research gaps. The agriculture sector in Uzbekistan contributes about 24% to the country's gross national product and generates job places for more than 25% of the workforce in Uzbekistan (UzStat 2021). The agriculture sector is facing multifaceted challenges due to climate change, inefficient management, and its Soviet legacy, which includes semi-centralized planning and supervision over the farms in Uzbekistan. These factors, in one way or another, affect the adoption of SAPs such as crop diversification, soil conservation, and efficient water use, as most of the time, the instructions and guidance are dictated by the government or proxy-government entities (e.g., Council of Farmers, agricultural clusters, and government-owned banks). By reviewing global and regional studies on agricultural innovation, decision-making theories, and institutional frameworks, the current review demonstrates the role of institutions as barriers as well as enablers in adoption of SAPs.

Agricultural innovation changed significantly over time and transformed from linear technology transfer models toward more collaborative and systemic methods as per the notion of Klerkx, van Mierlo, and Leeuwis (2012). According to them, there are three clusters in agricultural innovation research. The first cluster looks at agricultural advisory services and the historical development of innovation models. Back in 1950, extension services focused primarily on sharing technology from research communities to farmers. However, in 1980, it became clear that this was a complex process engaging several stakeholders and gradually shifted to the concept of Agricultural Knowledge and Innovation Systems (AKIS). The AKIS systems emphasized collaboration, knowledge sharing, and coordination among different actors in the innovation network. However, in the realities of Uzbekistan, institutional barriers such as land ownership issues and state-controlled crop plans hinder or at least slow down this progress. Ni, Akramov, and Fan (2024) note that despite post-Soviet reforms having allocated over 70% of arable land to individual farms, ongoing restrictions on production and marketing freedoms still limit innovation and result in a slow uptake of sustainable practices. This demonstrates that outdated institutional systems might restrict the shift to flexible, demand-driven adaptive, knowledge-based farming in Uzbekistan.

The second cluster in Klerkx, van Mierlo, and Leeuwis (2012) revolves around utility maximization theory, which views innovation adoption as a rational choice based on intrinsic value. In this context, the farmers are seen as decision-makers who evaluate innovations based on cost-benefit analysis and expected utility. Adams and Jumpah (2021) support this view by claiming that farmers choose options based on their expected utility function. Similarly, Klerkx, van Mierlo, and Leeuwis pointed out that adoption happens when the expected utility of an innovation surpasses that of keeping the status quo. However, institutional monopsony (agricultural clusters) in Uzbekistan limits this logical framework, where cost-benefit analysis is carried out at the cost of a farm's opportunity. Kurbanov, Djanibekov, and Herzfeld (2025) corroborate this idea by pointing out that most Uzbek farmers are subject to procurement regulations that force them to devote substantial amounts of land to particular crops in order to comply with government directives. Since established priorities frequently place more emphasis on quantity than on long-term environmental sustainability, established agreements between agriculture clusters and farmers restrict rational choices for sustainability and allow no option for crop rotation, a crucial SAP.

The third cluster broadens the conversation to include Feder and Umali's (1993) views on behavioral factors influencing the adoption of innovations, including SAPs per se. This stream of thought considers farmers' social networks, customs, beliefs, and perceptions, suggesting that technology that conflicts with these elements may encounter resistance. This aligns with the findings of Lamichhane et al. (2022) and Sumberg (2005), which indicate that different localities have different SAP adoption tactics because of climatic, environmental, and social issues, such as institutional limits, knowledge gaps, and economic barriers. Furthermore, despite SAPs' advantages and accessibility to farmers, their sustainable and long-term implementation requires an enabling environment that provides farmers with guidance and incentives to take SAPs into their farming operations. Such support might include well-structured knowledge networks, market access, and mechanisms for sharing experiences. In this regard, Nirmal and Babu (2023) point out the importance of collaborating with the public and private advisory services, loan options, subsidies, and training programs to encourage SAPs. Sikombe et al. (2024) also emphasized the need for community training and public-private partnerships in promoting adoption rates through demonstrations, pilot projects, and skill development programs. Despite multiple reforms in the agriculture sector, the current institutional system in Uzbekistan still resonates with the Soviet legacy, which frequently functions in a top-down fashion, making it difficult to respond to the real demands of farmers. Knowledge platforms are mostly found within networks of government agencies, GNGOs, and research institutes, according to Kurbanov et al. (2024). These entities centrally control innovation by dictating their own methods in vegetation primarily designed to achieve production targets, frequently overlooking or addressing farm-level demands in relation to innovation to a lesser extent. In contrast, agricultural clusters also provide farmers with access to investments, technology, and vital input resources (for example, seeds, fertilizers, and water access). However, as per Djanibekov, Herzfeld, and Petrick (2024), these clusters constrain farms' ability to negotiate, since agriculture clusters generate monopsony power limiting the bargaining advantage of the farmers. This dynamic maintains unsustainable practices associated with a quota system that reduces incentives for independent adoption of SAPs, reinforcing reliance on state-owned entities. In our view, successful SAP adoption requires integrating institutional, economic, and behavioral factors in a fair and well-coordinated manner, and long-lasting communication networks between advisory services and farmers are crucial for improving technical knowledge and encouraging SAP uptake among smallholders. In context of Uzbekistan, this means examining local institutions, cooperatives, extension services, and broader frameworks to better understand their role in adapting SAPs.

Lastly global studies provide more insights on factors influencing the adoption of SAPs by farms, but Central Asia's unique conditions usually remain unexplored, including post-Soviet institutional legacy and paired with resource limitations prevalent to Central Asian countries. Most existing literature tends to focus on contexts in Africa, Asia, or Europe, where institutional conditions differ from Uzbekistan's blend of state control and emerging market elements. For instance, Nirmal and Babu (2023) promote inclusive advisory systems, and Uzbekistan's GNGO-centric and rigid platforms suggest a need for research on hybrid models that empower farmers and smallholders. Similarly, the monopsony power of clusters, as per Djanibekov, Herzfeld, and Petrick (2024), illustrates a lack of understanding regarding power imbalances and their potential side effects on SAP adoption. Filling these gaps are objectives of this study, where more insights on the role of institutional factors in promoting adoption of multiple SAPs or otherwise are provided, thereby informing policy implications aimed at increasing farmers' autonomy, access to knowledge, and transitioning to sustainable agriculture in Uzbekistan.

In summary, theoretical frameworks such as AKIS and utility maximization provide valuable insights; however Uzbekistan's institutional context, characterized by procurement mandates, top-down knowledge systems, and reliance on agriculture clusters, might provide new and original insights to this study in the adoption of SAPs by Uzbek farmers.

3. Methodology

3.1 Data sources

This study is based on cross-sectional data collected in 2024, part of the UzFarmBarometer initiative. With observations from 1,225 managers of commercial farms, this nationally representative survey focused on agricultural practices and farmer behaviors across the Samarkand, Andijan, Khorezm, and Kashkadarya regions depicted in **Figure 1**. The dataset is rich with detailed information on household demographics, land ownership, farm characteristics, decision-making processes, and the use of SAPs, such as biopesticides, crop rotation, and sustainable manure application. The questionnaire includes both quantitative and qualitative variables. We organize them into several groups: 1) demographic, social, and behavioral characteristics; 2) institutional factors; and 3) farm-level attributes.

3.2 Theoretical framework

Farmers' adoption of SAPs can be framed as a sequence of interconnected choices under resource limitations, risk, and institutional factors. According to the conventional adoption theory, farmers compare expected utility from adopting an innovation versus maintaining status quo, and they will adopt only if perceived net benefits outweigh perceived adoption costs. This narrative aligns with diffusion research that emphasizes the perceived attributes of innovations (relative advantage, compatibility, complexity, trialability, observability) and the role of communication channels in accelerating learning and uptake (Rogers 2003). However, in Uzbekistan's agricultural system, characterized by agricultural clusters, production coordination, and district-level specialization, adoption decisions are not purely individual optimizations, but they are shaped by institutional 'rules of the game' that structure incentives, information access, and autonomy of decision-making. Institutions matter because they determine transaction costs (e.g., search, negotiation, compliance), the enforceability of land rights, and the extent to which farmers can choose inputs and crop-management strategies. From an institutional economics perspective, postulating North (1990), farmers' choices respond not only to prices and yields but also to formal constraints (contracts, quotas, cluster

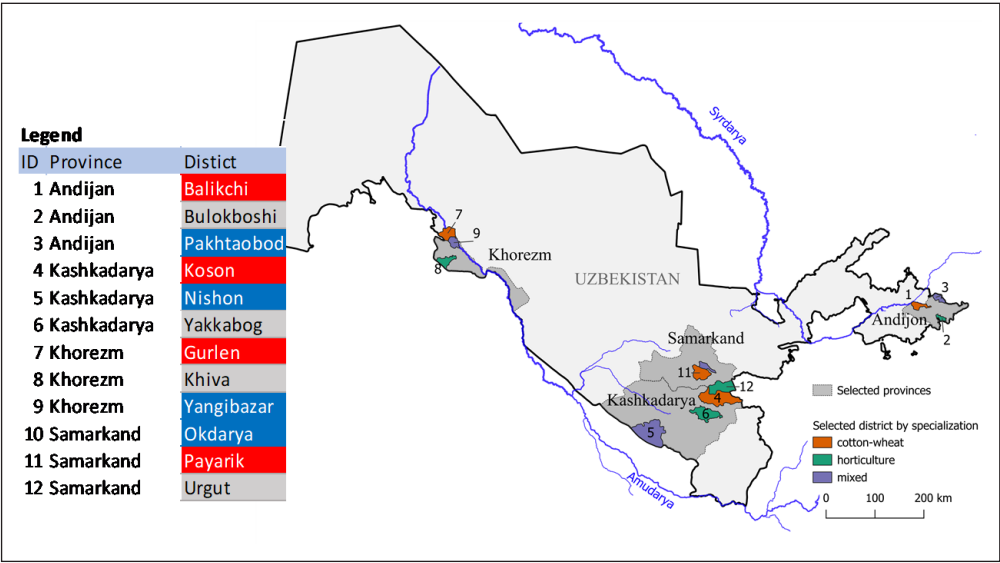


Figure 1: Map of survey regions.

Source: The map is formulated based on Quantum GIS (QGIS) using survey data from UzFarm-Barometer 2024.

requirements) and informal constraints (norms, localized expectations). Such institutions can either reduce uncertainty and enable investment, or lock farmers into specialized production pathways that limit experimentation.

A second domain concerns farmer agency and behavioral intention based on Ajzen's (1991) theory of planned behavior (TPB). The theory postulated that adoption behavior is driven by intention, which is shaped by attitudes, subjective norms, and perceived behavioral control. In the context of Uzbekistan, in an agriculture cluster-coordinated setting, subjective norms and control can be strongly influenced by higher organizations and extension agents in the hierarchy, meaning some practices may be adopted because they are promoted or required by coordinating institutions, while others may be suppressed if they conflict with specialization mandates or input packages. TPB, therefore, helps explain why 'autonomy of decision-making' and institutional pressure can have practice-specific effects rather than uniform impacts across all SAPs.

Knowledge and learning processes represent the third domain as identified by the European Commission and Standing Committee on Agricultural Research (SCAR) (2012, 45). The AKIS viewpoint highlights that the uptake of innovation relies on the quality and structure of knowledge networks that connect farmers with advisory services, training institutions, fellow farmers, and agribusiness stakeholders. Importantly, the emphasis is not only on the accessibility of training, but on whether farmers gain a variety of relevant and demand-driven knowledge that simplifies perceived complexity and uncertainty. Therefore, bundled training programs can enhance adoption of SAPs by enhancing technical skills, reducing perceived risk, and extending trusted networks, thereby transmitting innovations through peer-to-peer learning. These theoretical insights suggest that the adoption of SAP is multidimensional and encompasses an economic, a behavioral, and an institutional choice.

This integration is crucial for Uzbekistan, as decision-making autonomy is heterogeneous across farms and may be conditioned by cluster membership, contract obligations, and district specialization. In the future, extension of the autonomy of farmers should increase adoption of practices requiring on-farm coordination and long-term planning (e.g., manure management) by raising perceived behavioral control, while practices that are input-like and compatible with centralized procurement (e.g., biopesticides) may be less dependent on autonomy and more responsive to organizational promotion.

A central implication of this study is that SAPs are unlikely to be adopted independently, which is also according to Cappellari and Jenkins (2003), since binary outcomes are tied to latent variables, and the latter follow a multivariate normal distribution. And correlations between error terms capture interdependence among decisions. Therefore, biopesticides use, crop rotation, and sustainable manure use might be complements or substitutes. Crop rotation and manure both address soil fertility but differ in timing, labor requirements, and compatibility with crop-planning mandates. On the other hand, biopesticides may complement crop rotation if farmers pursue broader agroecological strategies, yet may substitute for manure-based soil health investments when liquidity or livestock access is limited. Because these practices share common constraints, knowledge access, risk preferences, autonomy, and institutional pressure, unobserved factors affecting one practice may be correlated with unobserved factors affecting another. This motivates a joint-adoption econometric framework that allows correlated errors across SAP adoption equations rather than assuming independence.

3.3 Empirical approach

To explore how multiple SAPs are adopted together, we use a MVP model. This approach is perfect for dealing with binary outcomes that might be linked, like adopting several practices at the same time. The MVP framework helps us manage unseen differences and possible correlations in error terms across different equations. This way, it prevents the results from being skewed or inefficient, as supported by Abay et al. (2017) and Teklewold, Kassie, and Shiferaw (2013).

Let Y_{ij} represent the latent utility or net benefit that farmer i derives from adopting sustainable agricultural practice j , where $j = 1, 2, 3, 4$ corresponding to:

- Biopesticide use (biopest: Yes = 1, No = 0)
- Crop rotation (crop_rot: Yes = 1, No = 0)
- Sustainable manure application (susmanr: Yes = 1, No = 0)

These latent variables are not observed directly. Instead, we observe the binary outcome:

$$Y_{ij} = \begin{cases} 1, & \text{if } Y_{ij}^* > 0 \\ 0, & \text{otherwise} \end{cases}$$

The latent variable Y_{ij}^* can be expressed as:

$$Y_{ij}^* = X_i' \beta_j + \epsilon_{ij}, j = 1, 2, 3$$

Where:

- X_i is a vector of explanatory variables for farmer i ,
- β_j is a vector of coefficients for practice j ,
- ϵ_{ij} is a normally distributed error term with zero mean.

The vector of error terms for farmer i , denoted as $\epsilon_i = (\epsilon_{i1}, \epsilon_{i2}, \epsilon_{i3})'$ is assumed to follow a multivariate normal distribution with zero mean and a covariance matrix Σ :

$$\epsilon \sim MVN(0, \Sigma)$$

where Σ is a symmetric 3×3 covariance matrix allowing for non-zero off-diagonal elements, reflecting the correlations among unobserved components of the SAP adoption decisions:

$$\Sigma = \begin{bmatrix} 1 & p_{12} & p_{13} \\ p_{12} & 1 & p_{23} \\ p_{13} & p_{23} & 1 \end{bmatrix}$$

The non-zero correlation coefficients, known as (p_{jk}) , estimate how different SAP adoption decisions are interconnected. This suggests that if one practice is influenced by certain unobserved factors, others might be too. By estimating these correlations, we can see if farmers' choices to adopt specific practices work together or in opposition. The model is formulated with three equations focusing on adopting biopesticides, crop rotation, and sustainable manure application, as seen in **Table 1**. Each of these equations includes the same set of factors: farmer age, education, experience, training diversity, off-farm income, farm size, land rights, risk aversion, and district-level specialization, detailed in **Table 2**.

Based on the existing literature and the specific context of Uzbekistan's agricultural sector, we hypothesize the following relationships between these variables and SAP adoption. Demographic, social, and behavioral characteristics, including age, gender, education, farming experience, and risk aversion, are expected to influence the adoption of SAPs. Education and farming experience are anticipated to have a positive effect, as better educated and more experienced farmers generally possess greater capacity to understand and implement new techniques (Thapa & Rattanasuteerakul 2011; Lapar & Ehui 2004). Conversely, age and risk aversion may exert a negative influence: older farmers often prefer traditional methods (D'souza, Cyphers, & Phipps 1993), while risk-averse individuals tend to avoid unfamiliar practices even when they offer long-term benefits (To-The et al. 2025). Gender effects are multifaceted. While labor-intensive SAPs may present barriers for female farmers, knowledge-based practices that rely on information sharing tend to be more inclusive. In addition, gender effects are likely to be context-specific, potentially varying with labor intensity and farm size, factors that shape the feasibility and attractiveness of adopting SAPs (Rizzo et al. 2024).

Institutional factors include exposure to training, land rights, and decision-making autonomy. We anticipate that greater exposure to training increases the likelihood of SAP adoption, establishing a positive relationship between training intensity and adoption levels. Similarly, secure land rights and greater autonomy in decision-making are expected to be associated with higher SAP adoption (Besley 1995; Nguyen 2019). We hypothesize that secure land rights encourage farmers to invest in long-term soil conservation measures, as they have stronger incentives to maintain and improve soil quality when future benefits will accrue to them.

Table 1: Description and definition of explanatory variables.

Variable	Description	Mean	SD
Farm-level characteristics			
farm_size	Total area of farm (in ha)	35.57	34.1
off_farm income	Farm manager has off-farm employment (yes = 1; no = 0)	0.15	0.36
new_technology	Willingness to adopt new production methods and technologies (1-Completely disagree; 5-Completely agree)	3.49	1.24
risk_aversion	Self-reported willingness to take risks (1-Completely unwilling; 5-Very willing)	3.31	1.69
sap_autonomy	Extent to which farmer feels lack of decision-making autonomy to cultivate SAPs (1-Strongly disagree; 5-Strongly agree)	2.87	1.28
Demographic, social, and behavioral characteristics			
farmer_age	Farm manager's age (in years)	45.93	10.28
gender_male	Farm manager's gender (male=1; female=0)	0.94	0.24
agricultural_education	Farm manager has special education in agriculture (yes = 1; no = 0)	0.6	0.49
farmer_experience	Farm manager's working experience in agriculture (in years)	15.84	8.91
Institutional characteristics			
training_diversity	Number of trainings a farmer has attended in the last 3 years	1.20	1.42
district_specialization	Main agricultural activity that the district specializes in (1-Cotton-wheat; 2-Mixed; 3-Horticulture)	1.99	0.82
land_rights	Perceived likelihood of losing land tenure rights within the next 3 years (0% = Definitely not lose; 100% = Certainly lose)	9.27	18.65
cluster_member	Is your farm a member of a cotton-textile cluster or agricultural cluster (yes = 1; no = 0)	0.52	0.49
Total number of observations		1225	

Source: Authors' elaboration using the farm survey data.

Farm-level characteristics define the economic and operational context of farms and include farm size, crop specialization, and off-farm income. We anticipate that larger farm size may reduce SAP adoption due to the higher associated cost of implementation (Feder, Just, & Zilberman 1985). Crop specialization is expected to hinder SAP adoption, as strict regulation of the production process by agricultural clusters and proxy-government structures limits

Table 2: Description and definition of dependent variables.

Variable	Description	Mean	SD
susmanr	Application of sustainable manure (yes = 1; no = 0)	0.17	037
croprot	Crop rotation for improving land fertility (yes = 1; no = 0)	0.52	0.20
biopest	Biological methods for pest control (yes = 1; no = 0)	0.04	0.49
Total number of observations		1225	

Source: Authors’ elaboration using the farm survey data.

farmers’ flexibility in changing established practices. Finally, off-farm income is anticipated to have a positive effect on adoption, as it provides farmers with additional financial resources to invest in soil conservation measures that may yield returns over the longer term (Huffman 1980; Ullah & Shivakoti 2014).

All the above-mentioned factors intertwine to shape how farmers perceive the benefits of SAPs and influence their willingness to adopt them. The study focused on the Samarkand, Andijan, Khorezm, and Kashkadarya regions in Uzbekistan, known for their diverse farming systems and different levels of involvement in state agriculture programs. These regions provide a valuable setting for exploring how different conditions affect the uptake of SAPs. By sampling farms across these diverse regions, the study captures variation in land tenure security, extension services, and regional specialization policies, giving a comprehensive view of the farming landscape.

We used simulated maximum likelihood with robust standard errors for consistent and efficient results, following the framework applied by Bilal and Jaghdani (2024) in their study of multiple agricultural technology adoption in Pakistan. Their findings on the importance of modeling practice interdependencies informed both our analysis structure and how we interpret the output.

4. Results

The descriptive summary of the response and explanatory variables is presented in **Tables 1** and **2**. In line with them, we include key institutional variables, socioeconomic and farm-level factors, as covariates in this study.

The results show a moderate implementation of different practices. Around 17% of farmers are using sustainable manure strategies, while nearly 4% are utilizing biological pest management approaches. Crop rotation is the most widely embraced sustainable farming method, with more than half of the farmers in the research integrating it into their practices. In respect to the farm managers’ backgrounds, the average age is 46 and about 16 years of farming experience, pointing to a well-established farming demographic. It seems the agriculture sector is dominated by males, making up 94% of this group, while 60% of the respondents received agricultural education. The data shows that most respondents’ occupation is farming, with only 15% having jobs outside of agriculture. Also, the size of the farms varies a lot, ranging from small plots of 0.4 hectares to large areas of 289 hectares, making the average farm size 35.6 hectares. Specialization in agricultural production differs across districts. There is an overall positive perspective on land tenure security for the next three years, with only a 9.3% perceived likelihood of losing land rights. However, regarding a decision-making autonomy about sustainable agricultural practices, the feedback is somewhat alarming, with an average

rating of 2.87 out of 5. In terms of attitudes toward agricultural innovation, farmers display a moderate eagerness for embracing new technologies, achieving an average score of 3.5, along with a fair level of risk tolerance indicated by a score of 3.31 out of 5.

Based on the key findings from **Tables 3, 4**, and Table A1 of our analysis of SAP adoption among Uzbek farmers, based on the 2024 UzFarmBarometer survey, we focus on three practices: sustainable manure management (susmanr), crop rotation (croprot), and biopesticide use (biopest). We begin with a probit model for each practice (**Table 3**), then move to an MVP model that accounts for the fact that farmers might not make these decisions in isolation; they often adopt practices simultaneously, as complements or substitutes (see Appendix, Table A1). Finally, we show the average marginal effects from the MVP model. These effects demonstrate how much each factor influences adoption probabilities (**Table 4**). All models include socio-demographic, farm, institutional, and behavioral factors.

4.1 Exclusive probit estimates

The findings of distinct probit regressions for every SAP adoption are presented in **Table 3**. According to the estimates, older farmers are somewhat more likely to adopt sustainable manure (susmanr) ($p < 0.05$). Conversely, farmers with more years of experience have a lower adoption rate ($p < 0.05$). Adoption seems to be strongly positively impacted by exposure to different training programs ($p < 0.01$). Also, adoption of sustainable manure is found to be facilitated by district specialization ($p < 0.01$) and membership in agricultural clusters ($p < 0.01$). However, the likelihood of adopting sustainable manure is reduced by large farms ($p < 0.01$) and likewise lower for farmers with less perceived autonomy over SAP decisions ($p < 0.01$). There is a slight but statistically significant increase in the adoption of sustainable manure ($p < 0.05$) among farmers who perceive they have safer land tenure perspectives. Overall, the model fit is significant ($\chi^2 = 101.301$, $p < 0.01$), and the model explains roughly 9.7% of the variation (pseudo- $R^2 = 0.097$).

The results for crop rotation (croprot) SAP differ notably from other practices. Age demonstrates a weak negative association with adoption ($p < 0.1$), and male farmers are significantly less likely to implement crop rotation ($p < 0.01$). In contrast, greater farming experience ($p < 0.01$) and increased training diversity ($p < 0.01$) are both positively associated with adoption. District-level specialization reduces the likelihood of adoption ($p < 0.05$), as do larger farm sizes ($p < 0.01$) and higher levels of risk aversion ($p < 0.05$). Perceived security of land rights continues to have a positive effect ($p < 0.01$). Despite the model exhibiting modest explanatory power (pseudo- $R^2 = 0.036$), it remains statistically significant in general and explains 60% of variations ($\chi^2 = 60.691$, $p < 0.01$).

The adoption of biopesticides demonstrates a distinct pattern. Older farmers are significantly more likely to use biopesticides ($p < 0.05$), and a broader range of training exerts a strong positive influence ($p < 0.01$). Conversely, greater farming experience, district specialization ($p < 0.05$), and higher risk aversion ($p < 0.01$) are associated with reduced adoption rates ($p < 0.1$). In addition, farmers who exercise greater autonomy in decision-making are more likely to adopt biopesticides ($p < 0.01$). In general, the model accounts for the data and adequately explains 11.2% variations (pseudo- $R^2 = 0.112$, $\chi^2 = 54.779$, $p < .01$).

In summary, separate models generate valuable initial insights, but they assume independent decisions in applying SAPs. However, such independence is improbable. Therefore, the following analysis estimates SAP adoption in a joint manner.

4.2 Multivariate probit estimates

The coefficients are close to those from the univariate probit models illustrated in **Table 3**, and overall support the findings. Table A1 (see Appendix) presents the MVP results, which estimate the three equations together and account for related errors. The estimated error

Table 3: Probit regression estimates of three exclusive probit models for SAP adoption.

Variable	susmanr	croprot	biopest
farmer_age	0.011** (0.005)	-0.009* (0.005)	0.015** (0.007)
gender_male	0.059 (0.186)	-0.422*** (0.152)	0.049 (0.271)
agricultural_education	0.039 (0.094)	-0.072 (0.078)	0.068 (0.15)
farmer_experience	-0.012** (0.006)	0.018*** (0.005)	-0.015* (0.009)
training_diversity	0.202*** (0.033)	0.084*** (0.027)	0.198*** (0.035)
off_farm	0.146 (0.122)	0.165 (0.102)	0.22 (0.184)
new_technology	0.01 (0.039)	-0.024 (0.031)	-0.005 (0.055)
district_specialization	0.206*** (0.056)	-0.098** (0.046)	-0.208** (0.084)
farm_size	-0.005*** (0.002)	-0.004*** (0.001)	0.002 (0.002)
land_rights	0.005** (0.003)	0.007*** (0.002)	-0.004 (0.004)
sap_autonomy	-0.147*** (0.033)	-0.024 (0.03)	0.172*** (0.058)
risk_aversion	0.01 (0.027)	-0.055** (0.022)	-0.131*** (0.038)
cluster_member	0.437*** (0.099)	0.089 (0.084)	0.051 (0.141)
Constant	-1.875 (0.344)	1.064 (0.3)	-2.385 (0.538)
Mean dependent var	0.170	0.522	0.044
SD dependent var	0.376	0.500	0.205
Pseudo r-squared	0.097	0.036	0.112
Chi-square	101.301***	60.691***	54.779***
Number of obs	1225	1225	1225

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, standard errors in parentheses.

Source: Author's calculations based on 2024 UzFarmBarometer data.

correlations (ρ) show how decisions are related. ρ_{12} (susmanr-croprot) = -0.310 ($p < 0.01$) and ρ_{13} (susmanr-biopest) = -0.446 ($p < 0.01$) both suggest substitution, while ρ_{23} (croprot-biopest) = 0.288 ($p < 0.01$) suggests complementarity. The likelihood ratio test rejects independence ($\chi^2 = 235.41$, $p < 0.01$), supporting the use of MVP instead of univariate probits, as observed by Abay et al. (2017).

As per sustainable manure, the main positive enabler for adoption is age ($p < 0.05$), training diversity ($p < 0.01$), district specialization ($p < 0.01$), land tenure perception ($p < 0.05$), and agriculture cluster membership ($p < 0.01$). The deterring factors in adopting are experience ($p < 0.05$), farm size ($p < 0.01$), and autonomy in decision-making ($p < 0.01$). For crop rotation, age has a slightly significant negative association ($p < 0.1$), and being male has a strong negative effect ($p < 0.01$) in adopting the SAP. On the other hand, experience ($p < 0.01$), training diversity ($p < 0.01$), and land rights security ($p < 0.01$) are found to be main enablers in adopting. District specialization ($p < 0.05$), farm size ($p < 0.01$), and risk aversion ($p < 0.05$) show negative associations. Biopesticide use adoption shows similar results, with positive effects from age ($p < 0.05$) and training diversity ($p < 0.01$). Negative associations include experience ($p < 0.1$), district specialization ($p < 0.05$), and risk aversion ($p < 0.01$). The autonomy in decision-making is also positively linked to adoption ($p < 0.01$).

4.3 Marginal effects

Table 4 presents the marginal effects from the MVP model. The analysis illustrates that each additional unit of training diversity increases the chance of adoption by 1.6 percentage points ($p < 0.01$) for biopesticide use. Similarly, additional farmer age adds 0.1 percentage points ($p < 0.05$), and decision-making autonomy adds 1.3 percentage points ($p < 0.01$) for biopesticide use. In contrast, district specialization reduces adoption by 1.6 percentage points ($p < 0.05$), risk aversion by 1.1 percentage points ($p < 0.01$), and additional year of experience by 0.1 percentage points ($p < 0.1$). With regard to crop rotation, training diversity increases the probability of adoption by 3.2 percentage points ($p < 0.01$), additional year of experience by 0.7 percentage points ($p < 0.01$), and land tenure perception by 0.3 percentage points ($p < 0.01$). In contrast, male farmers are 16.6 percentage points less likely to adopt ($p < 0.01$) crop rotation, and additional age of farmers lowers the probability by 0.3 percentage points ($p < 0.1$), district specialization by 3.8 percentage points ($p < 0.05$), farm size by 0.2 percentage points ($p < 0.01$), and risk aversion by 2.1 percentage points ($p < 0.05$). Lastly, for sustainable manure, estimations exhibit that additional training diversity increases adoption by 4.4 percentage points ($p < 0.01$), district specialization by 4.7 percentage points ($p < 0.01$), and agriculture cluster membership by 9.9 percentage points ($p < 0.01$). Moreover, additional aging of a farmer surges adoption by 0.3 percentage points ($p < 0.05$), and added extra land tenure increases adoption by 0.1 percentage points ($p < 0.05$). Conversely, the deterrents include less perception of autonomy in decision-making, decreased adoption by 3.3 percentage points ($p < 0.01$), farm size by 0.1 percentage points ($p < 0.01$), and additional experience by 0.3 percentage points ($p < 0.05$), respectively. These results demonstrate that training diversity plays a key role, while factors like decision-making autonomy and land tenure affect each practice differently depending on the type of SAP.

5. Discussion

The empirical evidence indicates that the adoption of SAPs in Uzbekistan is formulated by socio-demographic, farm-level, institutional, and behavioral factors, with institutional influences being particularly noticeable. The findings support previous narratives that systemic approaches to sustainability extend beyond purely technical paradigms (Klerkx, van Mierlo, & Leeuwis 2012). The estimations indicate that the positive effects of training diversity, perceptions of decision-making autonomy, and land tenure align with existing research on the role of

Table 4: Marginal effects of the MVP model.

Variable	susmanr	croprot	biopest
farmer_age	0.003** (0.005)	-0.003* (0.005)	0.001** (0.007)
gender_male	0.022 (0.191)	-0.166*** (0.156)	0.008 (0.274)
agricultural_education	0.008 (0.095)	-0.026 (0.078)	0.004 (0.148)
farmer_experience	-0.003** (0.006)	0.007*** (0.005)	-0.001* (0.009)
training_diversity	0.044*** (0.031)	0.032*** (0.027)	0.016*** (0.035)
off_farm	0.033 (0.121)	0.061 (0.103)	0.018 (0.185)
new_technology	-0.000 (0.038)	-0.009 (0.031)	-0.002 (0.054)
district_specialization	0.047*** (0.056)	-0.038** (0.047)	-0.016** (0.082)
farm_size	-0.001*** (0.002)	-0.002*** (0.001)	0.000 (0.002)
land_rights	0.001** (0.002)	0.003*** (0.002)	-0.000 (0.004)
sap_autonomy	-0.033*** (0.033)	-0.008 (0.030)	0.013*** (0.055)
risk_aversion	0.003 (0.027)	-0.021** (0.023)	-0.011*** (0.038)
cluster_member	0.099 (0.099)	0.033 (0.084)	0.005 (0.138)
Number of obs	1225	1225	1225

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, standard errors in parentheses.

Source: Author's calculations based on 2024 UzFarmBarometer data.

institutional features in framing adoption behaviors of Uzbek farmers. Among all regressors, training diversity is a significant determinant, increasing the likelihood of adoption across all SAPs (biopesticide use: 1.6 percentage points, $p < 0.01$; crop rotation: 3.2 percentage points, $p < 0.01$; sustainable manure: 4.4 percentage points, $p < 0.01$). This result is consistent with the literature suggesting that comprehensive training enhances innovation diffusion by improving competencies and confidence (Sikombe et al. 2024; Ma & Rahut 2024) of farmers. Within Uzbekistan's evolving sustainable agriculture sector, diverse engagement through extension services and knowledge networks, as described in the AKIS framework, is more effective than existing training platforms.

Perceptions of decision-making autonomy around SAPs have mixed effects, indicating that in the case of biopesticide use (1.3 percentage points, $p < 0.01$) it increases, reduces sustainable manure adoption (−3.3 percentage points, $p < 0.01$), and has little impact on crop rotation. Such a mixed effect comes from agricultural clusters supervision, since in the first case they allow farmers to use it and in the second case deterring it. This mix matches research showing that institutional incentives can spur specific innovations, but sustained adoption requires alignment with farmers' agency and beliefs (Feder & Umali 1993; Bilal & Jaghdani 2024) and monopsony power of the agriculture clusters (Djanibekov, Herzfeld, & Petrick 2024). Lower autonomy likely means that external mandates drive biopesticide use, while adopting sustainable manure seems to be sanctioned by agriculture clusters or has intrinsic motivation or traditional value for farmers, underlining the need for policies that empower farmers in this regard.

Perceived land tenure is linked to higher adoption of crop rotation (0.3 percentage points, $p < 0.01$) and sustainable manure (0.1 percentage points, $p < 0.05$), but not biopesticide use. Although less land tenure perception should lead to lower long-term investment, the findings suggest farmers worried about risk may adopt immediate soil preservation practices (Totin et al. 2018). Further, district specialization arrangements support the adoption of sustainable manure (4.7 percentage points, $p < 0.01$), but undermine biopesticide use (−1.6 percentage points, $p < 0.05$) and crop rotation (−3.8 percentage points, $p < 0.05$). This may reflect that crop rotation is less feasible for perennial systems, so manure is favored to maintain soil fertility. Conversely, low biopesticide use suggests continued dependence on chemicals in specialized systems (Bobojonov et al. 2013). Interestingly, risk aversion lowers adoption of all practices (biopesticide: −1.1 percentage points, $p < 0.01$; crop rotation: −2.1 percentage points, $p < 0.05$), pointing to a need for risk-mitigation policies (Spiegel, Britz, & Finger 2021).

Further, socio-demographic variables illustrate different implications. For instance, age promotes biopesticide (0.1 percentage points, $p < 0.05$) and sustainable manure adoption (0.3 percentage points, $p < 0.05$), but discourages crop rotation (−0.3 percentage points, $p < 0.1$) method. It means older farmers might be reluctant to apply SAPs due to well-established resistance to new innovations and operate under their traditional knowledge per se (Djanibekov et al. 2018). In addition, it turns out that experience opposes biopesticide (−0.1 percentage points, $p < 0.1$) and sustainable manure (−0.3 percentage points, $p < 0.05$) use, but promotes the crop rotation (0.7 percentage points, $p < 0.01$) method. Interestingly, male farmers are much less likely to adopt crop rotation (−16.6 percentage points, $p < 0.01$). Also, larger farms adopt less crop rotation (−0.2 percentage points, $p < .01$) and sustainable manure (−0.1 percentage points, $p < 0.01$), since both practices are associated with labor-intensive investments. Agriculture cluster membership strongly supports sustainable manure adoption (9.9 percentage points, $p < 0.01$), highly likely due to perceived value of soil fertility, which should lead to higher yields.

Lastly, strong correlations among error terms ($Q_{12} = -0.310$, $p < 0.01$; $Q_{13} = -0.446$, $p < 0.01$; $Q_{23} = 0.288$, $p < 0.01$) demonstrate that decisions are interrelated: sustainable manure substitutes both crop rotation and biopesticide use, while crop rotation complements biopesticide use. It fits into the utility maximization theory; farmers weigh costs, resources, and trade-offs in decision-making (Feder & Umali 1993; Ruzzante, Labarta, & Bilton 2021) regarding the adoption of SAPs. In summary, advancing the diffusion of SAPs requires expanding training diversity, strengthening and extending farmer autonomy in decision-making and land tenure, relaxing crop mandates, and providing risk-mitigation approaches for farmers in Uzbekistan.

6. Conclusion

This study examines the determinants of SAP adoption among Uzbek farmers, focusing on manure management, crop rotation, and biopesticide use, based on the 2024 UzFarmBarometer survey. These adoption choices are interrelated and shaped by individual, farm, institutional, and behavioral factors, with institutional elements most influential.

Provision of diverse training opportunities for farmers is a significant adoption enabler across all SAPs. It seems participation in extension activities, workshops, or knowledge-sharing programs is linked with a higher likelihood of adopting sustainable manure management, crop rotation, and biopesticide use. This result demonstrates the effectiveness of interactive, multi-channel learning, as per AKIS principles, compared to traditional, top-down technology transfer methods (Ma & Rahut 2024; Sikombe et al. 2024). In Uzbekistan, where SAPs are under development, expanding, and diversifying, farmer education networks may be key to promoting change. The analysis also reveals nuances and barriers to adoption. Perceived decision-making autonomy in SAP-related matters has a dual effect. In one hand, it boosts biopesticide adoption but discourages sustainable manure management. This is probably due to the effect of cluster membership, where farmers are instructed to apply biopesticide use for certain crops to prevent the loss of production, compromising soil health (Kurbanov et al. 2024). Extended land tenure perceptions promote crop rotation and manure management, suggesting that farmers respond strategically to uncertainty, rather than always avoiding investment under insecure tenure (Totin et al. 2018). District-level crop specialization, common in Uzbekistan due to historical planning, encourages the use of manure in horticultural and mixed systems but limits the adoption of crop rotation and biopesticides. Risk aversion also consistently reduces the likelihood of adopting these practices (Spiegel, Britz, & Finger 2021; Bobojonov et al. 2013). In addition to this, socio-demographic factors influence adoption in its own way. For instance, older farmers are more likely to adopt biopesticides and manure management, challenging the view that age limits change (Djanibekov et al. 2018). Experience aids crop rotation but no other SAPs. Agriculture cluster membership increases manure management adoption.

The MVP model shows these practices are interdependent, indicating that some are substitutes while others are complements. Hence, in our view, adoption of SAPs in the context of Uzbekistan should be considered as part of integrated farm strategies, not isolated decisions from each other (Feder & Umali 1993; Ruzzante, Labarta, & Bilton 2021; Abay et al. 2017) to ensure their sustainable uptake. Limitations of the study include reliance on cross-sectional data, which reveal associations but not causality or changes over time. Unmeasured attitudes or regional differences may also influence results, despite the model's controls. Also, the study does not fully address biophysical factors or assess impacts of SAP adoption on yields, soil, or income, which require more robust data or experimental designs that should be the subject of the next research agenda.

Appendix

Table A1: MVP regression estimates of the joint SAP adoption decisions.

Variables	susmanr	croprot	biopest
farmer_age	0.011** (0.005)	-0.009* (0.005)	0.015** (0.007)
gender_male	0.096 (0.191)	-0.435*** (0.156)	0.099 (0.274)
agricultural_education	0.034 (0.095)	-0.067 (0.078)	0.046 (0.148)
farmer_experience	-0.013** (0.006)	0.018*** (0.005)	-0.015* (0.009)
training_diversity	0.195*** (0.031)	0.083*** (0.027)	0.194*** (0.035)
off_farm	0.146 (0.121)	0.160 (0.103)	0.219 (0.185)
new_technology	-0.000 (0.038)	-0.024 (0.031)	-0.024 (0.054)
district_specialization	0.208*** (0.056)	-0.098** (0.047)	-0.193** (0.082)
farm_size	-0.005*** (0.002)	-0.004 (0.001)	0.002 (0.002)
land_rights	0.006** (0.002)	0.007*** (0.002)	-0.003 (0.004)
sap_autonomy	-0.143*** (0.033)	-0.022 (0.030)	0.158*** (0.055)
risk_aversion	0.014 (0.027)	-0.055** (0.023)	-0.127*** (0.038)
cluster_member	0.434*** (0.099)	0.087 (0.084)	0.062 (0.138)
constant	-1.885 (0.348)	1.079 (0.302)	-2.329 (0.512)
Wald chi2(39)			235.41***
Number of obs			1225
atanhrho_12			-0.321***
atanhrho_13			-0.479***
atanhrho_23			0.297***
rho_12			-0.310***
rho_13			-0.446***
rho_23			0.288***

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, robust standard errors in parentheses. rho indicates the correlation coefficients among farming households' adopted farming practices; number of random draws ($R = 150$).

Source: Author's calculations based on 2024 UzFarmBarometer data.

Data Availability

The data for this study is available upon reasonable request from the corresponding author.

Competing Interests

The authors have no competing interests to declare.

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